Chartered Institute of Ergonomics & Human Factors

Andy Imada
IEA Awards Committee Chair

28 April 2015

Dear Andy

IEA Fellowship Nomination – Maury Nussbaum

In my capacity as Chair of the Chartered Institute of Ergonomics and Human Factors Honours Committee and Immediate Past President of CIEHF, I am pleased to forward a nomination form, CV and letters of support for Maury Nussbaum. Maury is currently a Fellow of CIEHF and has been a member for over 20 years.

My personal knowledge of Maury's distinguished contribution to ergonomics at an international level is through his work as a researcher, author, reviewer and journal editor. As the Editor-in-Chief of *Ergonomics* I can report that Maury has been a regular and respected author with this journal on a wide range of topics, publishing articles well-cited by and influential with other researchers. Maury has also been an Editorial Board member for as long as I can remember and a valued reviewer. A particularly notable achievement has been Maury's role as the founding editor of the new journal in our field *IIE Transactions on Occupational Ergonomics and Human Factors*, published by Taylor and Francis. The challenge of launching a new journal in current times cannot be understated.

Maury's application, CV and letters of support indicate his significant contribution in other areas of his work as a scholar and educator.

I believe Maury would be a deserving recipient of an IEA Fellowship.

Yours sincerely

Roger Haslam

Professor Roger Haslam, PhD

Chair, Honours Committee

INVESTORS IN PEOPLE

NOMINATION FORM FOR IEA FELLOW AWARD 2015

For use by IEA Member Societies to nominate an individual for the IEA Fellow Award

Submission Instructions:

Please complete this form electronically and e-mail as an attachment (together with other attachments such as CV, letters of support, etc.) to: **PastPres@iea.cc**

Deadline: May 1, 2015

Nominee for IEA Fellow

Full Name (and title):	Maury A. Nussbaum: H.G. Prillaman Professor of Industrial and Systems Engineering, Virginia Tech
Address:	250 Durham Hall (0118), Blacksburg, VA 24061, USA
E-mail:	nussbaum@vt.edu
Fax:	(1) 540-231-3322
Tel:	(1) 540-231-6053

Person submitting nomination

Name:	Professor Roger Haslam: Chair, Honours Committee of the IEHF
Address:	Chartered Institute of Ergonomics & Human Factors, Elms Court, Elms Grove, Loughborough, Leics. LE11 1RG
E-mail:	R.A.Haslam@lboro.ac.uk
Fax:	
Tel:	01509 234904

The Nomination

Basis for nomination To be considered for IEA Fellow Award, the nominee must meet both eligibility and distinction criteria. Please complete parts 1 and 2, below. Note that the eligibility criteria are used to screen candidates and do not hold much weight in the final decision.

1. **Eligibility.**

   Only candidates that meet the two eligibility criteria will be considered for the award. The candidate must have been a Full Member in good standing of a Federated or Affiliated

Ergonomics Society for at least the preceding **10 years**, and the candidate must have served the ergonomics community at an international level. International service means activities including service to the IEA, and an extensive publication record in international journals or international consulting or service to the United Nations organizations, or similar. Describe below the nominee's service to the society, the IEA, and the ergonomics profession. *Please type your response within the box and it will expand, as necessary. There is no space limit.*

Society Memberships:

Continuous member of the HFES since 1994 (currently a Full Member)

Continuous member of the Ergonomics Society / IEHF since 1994 (currently a Fellow)

Service to the ergonomics community (highlights):

- Teaching:
  - Instructor for over 350 graduate students (including over 100 students from outside the U.S.), as instructor of an MS-level course entitled "Human Physical Capabilities" (covering occupational ergonomics, occupational biomechanics, and work physiology)
  - Instructor for nearly 500 undergraduate students, as instructor of a BS-level course entitled "Industrial Ergonomics"
- Advising/Mentoring:
  - Primary or co-advisor for 25 PhD students, including 12 from outside the U.S.
  - Primary advisor or co-advisor for 19 MS students, including 6 from outside the U.S.
  - Hosted/mentored seven post-doctoral researchers (6 from outside the U.S.), and 8 visiting researchers or research scholars (7 from outside the U.S.)
- Publication Record:
  - Author/co-author of 147 papers in peer-reviewed archival journals; nearly all addressed issues in or related to ergonomics, and all journals have an international audience and/or authors.
  - Author/co-author of 153 papers/abstracts at national and international conferences.
- Service to professional societies:
  - Editorial board member and regular reviewer for: *Journal of Occupational and Environmental Hygiene* (since 2004), *Ergonomics* (since 2006), *Applied Ergonomics* (since 2009)
  - Regular reviewer (nearly every year for the past decade) of conference papers submitted the annuals meetings of the HFES and IEHF
  - Founding and managing editor of the *IIE Transactions on Occupational Ergonomics and Human Factors*.
  - Special issue co-editor for two special issues in international journals

- Special service to promote/enhance ergonomics and human factors in Industrial Engineering (through the Institute of Industrial Engineers): founding journal editor (as noted above); Track Chair, Human Factors and Ergonomics at the Industrial Engineering Research Conference; Program Committee Member (2 years) for the IIE Applied Ergonomics Conference.

2. Distinction.

Eligible candidates will be evaluated on the basis of demonstrated outstanding theoretical or applied contributions to ergonomics/human factors. There are many ways in which this contribution can be demonstrated. The candidate could have had the primary responsibility for the technical direction, supervision or management of a significant effort during a sustained period of time. The candidate could be a renowned researcher, designer, or consultant of great distinction.

Clear evidence of distinction should be supported by detailed descriptions and attachments. For example, for a researcher, the most significant publications authored or co-authored by the candidate should be attached to the application. For a consultant, the most important consulting contracts should be outlined, together with the outcome of the contracts. For a designer the most important design objects should be specified. Any other information to support or attest to the achievements of the candidate should be furnished to the IEA Awards Committee, in order to support their deliberation of the candidate's merits.

Summarize in the space below the candidate's qualification for the prestigious IEA Fellowship.

The primary focus of Dr. Nussbaum's work is on occupational injury prevention, including developing and improving methods to assess occupational exposures to injury risk factors, enhancing approaches to assess occupational injury risks, and developing/evaluating guidelines, methods, and interventions for ergonomics practice. He is an industrial engineer and mechanical engineer by training, and focuses on occupational biomechanics and physical ergonomics. His work is mainly directed to understanding and controlling musculoskeletal disorders and fall risks, and doing so among diverse populations (e.g., related to age, gender, and obesity). He has made important contributions at both basic and applied levels, and in five primary domains that are each summarized below. He is perhaps best known in the ergonomics community for his work in the first two of these domains: localized muscle fatigue and occupational biomechanics. His overall scholarly contribution has been substantial, with over 140 peer-reviewed papers in international archival journals (including *Applied Ergonomics*, *Ergonomics*, *Human Factors*, and the *International Journal of Industrial Ergonomics*. His work has been well recognized by others, as evidenced by a total of >2,700 citations (>1,800 since 2010), an h-index of 30, and an i10 index of 77 (via Google Scholar). Four sample publications are included, each of which has been cited over 50 times.

First, he has published extensively on the topic of localized muscle fatigue. This work has addressed several basic questions regarding measuring such fatigue, such as the effectiveness of different processing methods for electromyographic signals. More practically, his work has assessed the effects of different task factors on fatigue development, generated predictive models effects, used fatigue as the basis for developing recommended occupational guidelines, assessed the influence of aging and obesity on fatigue development, and contributed to understanding the complex and interactive effects of physical and mental workload on both fatigue and performance.

Second, he has made important contributions in the area of occupational biomechanics, specifically as it relates to assessing mechanical demands at the low back. His early work presented new modeling approaches to address the geometric complexity of the spine and musculature as well as to understand and predict muscle recruitment strategies, and also developed and applied new models to predict loading on the lumbar spine during complex occupational activities. More recently, he has examined the mechanical and physiological mechanisms whereby prolonged/repetitive trunk flexion might contribute to an increased risk of occupational low back pain.

Third, he has developed and applied methods to accurately assess ergonomic exposures and injury risks during a variety of physically-demanding occupational tasks. Such methods have largely focused on whole-body kinematics and kinetics, particularly at often-injured body regions such as the low back and shoulders. A variety of approaches have been used, ranging from theoretical models to wearable sensors for field application. These have been applied to range of tasks in several occupational domains, such as automotive assembly, patient handling, and residential construction. One notable example is his recent work on residential construction. In this, he and his colleagues completed extensive field observations, constructed lab-based recreations of diverse tasks, and used a variety of analysis methods to assess exposures and potential injury risks.

Fourth, he has been working for several years to measure and model human postural control (or, balance ability), to understand what affects postural control and/or might increase fall risks, and to develop/evaluate approaches or interventions to minimize fall risks. Completed work has quantified the effects of fatigue on postural control, assessed methods to model and simulate human balance performance, and evaluated the efficacy of potential interventions. His ongoing work is examining the adverse effects of fatigue, load carriage, and aging on the risks of slips and post-slip recovery, the influences of aging and obesity on the risks of slips and trips, and the potential implications of these effects and influences on existing safety guidelines.

Fifth, he has completed several projects related to consumer product design and usability. Such projects have addressed several aspects of cellular phone design, including fundamental contributions to assessment and evaluative methodologies. Extensive work has also used subjective and objective responses to assess automotive seating, with contributions including new data acquisition and processing methods and specific data and recommendations for use in future seating designs.

A substantial portion of his work, such as summarized above, has focused on what may be considered more basic research questions. However, he has also generated a number of more directly applicable and practical contributions. For example, several papers have reported on studies designed to facilitate new or revised guidelines for ergonomic practice. In some cases, the data were clearly presented in such a form as to allow direct application to industry. In others, the emphasis was instead on whether a given aspects of a task, workstation, product, or work organization was likely to be influential. Such work can be used by both practitioners and researchers to better understand what are most likely to be influential work aspects, for example in terms of injury risks or performance, and to help guide the evaluation or design of specific work tasks. Examples of such outputs include: 1) guidelines for hand-intensive tasks and overhead work; 2) assessments of the role of individual differences such as age, gender, and obesity on job performance and injury risks; and 3) identification of important design aspects related to job-rotation schemes.

Additional Information:

The nominee's curriculum vitae should be electronically appended to the nomination. Other supporting documents such as scientific papers or other evidence may also be attached.

Electronic versions of Dr. Nussbaum's CV and a sample of scientific papers (listed below) are included with the nomination package.

- Barker, L.M. and Nussbaum, M.A. (2011) Fatigue, performance, and the work environment: a survey of registered nurses. *Journal of Advanced Nursing*, 67, 1370-1382.
- Kyung, G. and Nussbaum, M.A. (2008) Driver sitting comfort and discomfort (part II): relationships with and prediction from interface pressure. *International Journal of Industrial Ergonomics*. 38, 526-538.
- Nussbaum, M.A., Chaffin, D.B. and Rechtien, C.J. (1995) Muscle lines-of-action affect predicted forces in optimization-based spine muscle modeling. *Journal of Biomechanics*, 28, 401-409.
- Yassierli, Nussbaum, M.A., Iridiastadi, H. and Wojcik, L. (2007) The influence of age on isometric endurance and fatigue is muscle dependent: a study of shoulder abduction and torso extension. *Ergonomics*. 50, 26-45.

Endorsement by a Federated Society

(Note that many nominees belong to several ergonomics societies. The endorsement can come from any of these societies)

Name of endorser:	Professor Roger Haslam
Position held:	Chair, Honours Committee
Name of Federated Society:	IEHF

Letters of support (optional)

(Letters may be written by persons from the same society or other societies, but they are not required for the nomination. Supporting letters should be attached to the nomination submission. The names of individuals supporting the nomination should be listed below)

1. Name of endorser: Hardianto Iridiastadi, PhD; Yassierli, PhD; Khoirul Muslim, PhD
   Positions held: Faculty, Department of Industrial Engineering, Institut Teknologi Bandung, Indonesia
   Name of Federated Society: Indonesian Ergonomics Society

2. Name of endorser: Professor Massimiliano Pau, PhD
   Position held: Chair of Mechanical Bioengineering, Department of Mechanical, Chemical and Materials Engineering, University of Cagliari, Italy
   Name of Federated Society: none

3. Name of endorser: Dr. Jim Potvin
   Position held: Professor, Department of Kinesiology, McMaster University, Canada
   Name of Federated Society: Association of Canadian Ergonomists and HFES

4. Name of endorser: Ms. Allison Stephens
   Position held: Technical Leader, Global Ergonomics Manager, Ford Motor Company
   Name of Federated Society: none

5. Name of endorser: Dr. G. Don Taylor
   Position held: Department Head, Industrial and Systems Engineering, Virginia Tech, USA
   Name of Federated Society: none

6. Name of endorser: Mr. Kei Tomioka
   Position held: Senior Manager, Design Management Department, Toshiba Corp., Tokyo, Japan
   Name of Federated Society: Japan Ergonomics Society

LABORATORY FOR WORK SYSTEM DESIGN & ERGONOMICS
THE DEPARTMENT OF INDUSTRIAL ENGINEERING
FACULTY OF INDUSTRIAL TECHNOLOGY
INSTITUT TEKNOLOGI BANDUNG - INDONESIA

April 21, 2015

International Ergonomics Association

To Whom It May Concern,

We are very pleased to recommend Maury Nussbaum, Ph.D. for the IEA fellow position that he is applying for. We have known Dr. Nussbaum for many years, and had the pleasure of being a doctoral student under his guidance. We greatly appreciate Dr. Nussbaum's help in providing the support and fundings for our program.

With his continuing support, we lead and helped the Indonesian Ergonomics Society (IES) become a member of the IEA and an active member of the South East Asia Network of Ergonomics Society (SEANES). As faculty members in the Industrial Engineering Department, Institut Teknologi Bandung (ITB), we have improved ergonomics curriculum in Indonesia, and begun to extensively apply ergonomics principles for various industrial sectors. We also have the state of the art technology for ergonomics research that, in this field, makes ITB as the leading institution in the country. All these have been made possible with Dr. Nussbaum's involvement and guidance.

Through Dr. Nussbaum's effort, we were able to finish postdoctoral activities back in the U.S. From such program, we were able to publish an ergonomics textbook that is now being used nationally. Moreover, we are able to publish our work in a number of internationally recognized journals. Recently, Dr. Nussbaum and us have just conducted a research collaboration, addressing manual handling among Indonesian workers in the logistics sector.

To us, he is an individual with outstanding international influence. Without reservation, we strongly recommend Dr. Nussbaum for this IEA fellow position. We certainly believe that such a position will substantially further his international contribution.

Sincerely,

Hardianto Iridiastadi, Ph.D.
(Associate Professor)

Yassierli, Ph.D.
(Associate Professor)

Khoirul Muslim, Ph.D.
(Assistant Professor)

UNIVERSITY OF CAGLIARI

DEPARTMENT OF MECHANICAL, CHEMICAL AND MATERIALS ENGINEERING

Chair of Mechanical Bioengineering
Laboratory of Biomechanics and Industrial Ergonomics

Prof. Massimiliano Pau, PhD

Cagliari (ITALY), April 14, 2015

<u>To whom it may concern</u>

I am happy to support the nomination of Maury Nussbaum as a fellow in the IEA. My first contact with Prof. Nussbaum dated back 2010, knowing that he was a recognized expert in the field of Ergonomics, in particular as regards the study of standing and sitting postures. I was specifically interested in having him participate as a consultant for several projects that our Department was planning to start at that time. At our University there are no actual experts in Ergonomics, nor any specific courses at either the undergraduate and graduate levels. As such, we approached Prof. Nussbaum in the hope that he would provide strong initial support for the design of our experiments as well as for subsequent data analysis and interpretation.

He was very kind indeed, and agreed to cooperate with us. As a result of this partnership, a number of papers were published within international journals, especially in the field of postural assessment of young and adult individuals in fatigued conditions.

In 2012, Prof. Nussbaum was invited as a Visiting Professor at the University of Cagliari. During his stay here, he gave a short course on "Principles of Ergonomics" to our B.Sc. students in Biomedical Engineering. This was very well received by the students, several of whom developed a sincere interest in this field. He also shared some of his work with researchers and professors of my University.

The scientific collaboration between the Laboratory of Biomechanics and Industrial Ergonomics (for which I'm responsible) and Prof. Nussbaum is still active and several researches are currently ongoing.

I'm particularly grateful to Prof. Nussbaum as he played an essential role in the development of research in the field of Ergonomics in our University. Because of this, and his numerous other contribution to the field, I thus strongly support his nomination as an IEA fellow.

If I can be of further assistance, please feel free to contact me.

Yours faithfully

Massimiliano Pau, PhD

Phone +39-070-6753264
Fax +39-070-6755717
Email: massimiliano.pau@dimcm.unica.it

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April 26, 2015

To: International Ergonomics Association

From: Dr. Jim R. Potvin
Professor, Department of Kinesiology, McMaster University

Re: Dr. Maury Nussbaum
Application for Fellow status in the International Ergonomics Association

To whom it may concern

I am very pleased to endorse Dr. Maury Nussbaum's application to become a Fellow of the International Ergonomics Association. I am a Professor in the Department of Kinesiology at McMaster University and am a member of the Association of Canadian Ergonomist (ID: 71709) and the Human Factors and Ergonomics Society (ID: 37262).

Dr. Nussbaum's impact on the field of ergonomics is very substantial and diverse. I can honestly say that his breadth of expertise, as well as his scientific, service and training contributions, are among the most impressive that I have ever seen in the field. His range of interests and research publications is truly remarkable. He has contributed to physical ergonomics in areas like: peripheral muscle fatigue, aging effects on low back pain, balance and falls in the elderly, construction, patient handling, joint stability, trunk biomechanics, power tools, prolonged sitting, obesity, disabilities (amputation, military trauma), psychophysics, posture prediction, manual materials handling, head-worn displays, dynamic hand impacts, logging, tissue damage markers, keyboards, tissue mechanics and assistive devices. He has also contributed to knowledge regarding occupational health and safety (slips and falls, protective clothing, effects of pesticides on posture, immigrant worker health) as well as cognitive ergonomics (computer and electronic device interfaces, mental workload, decision processes, driving, usability). Maury has also moved the field forward with his use (and published explanations) of alternative methods in ergonomics, such as: artificial neural networks, fuzzy logic, Lyapunov exponents, electromyography, principle components analysis, cumulative probability distributions, decision modeling, wobbly mass, inertial sensors, wavelets and bootstrapping. This research has produced 147 publications, 153 conference proceedings and 5 book chapters. Personally, I always make sure that I am alerted to his latest publications.

DEPARTMENT OF KINESIOLOGY
1280 Main Street West, Hamilton, Ontario, L8S 4K1
(905) 525-9140 ext 23004, fax (905) 527-3071

In addition to his research output, Dr. Nussbaum is also an excellent mentor and educator at Virginia Tech University. He has made substantial contributions to ergonomics and occupational biomechanics training at Virginia Tech (8 courses on a total of 35 occasions). Has supervised, or co-supervised, 25 PhD students, and is currently supervising 8 more. Almost all went on to careers in academia and/or research related to ergonomics. He has also directed 19 Masters students. I also know that he is an excellent mentor to young faculty at VTU, and I have always appreciated how much he has done for a past graduate of mine, Dr. Mike Agnew, since his arrival on faculty there in 2007.

Finally, Maury has been very active in service to the discipline of ergonomics, both nationally and internationally. He reviews for a large number of journals and serves on the Editorial Board for journals in ergonomics, biomechanics and industrial hygiene. He is also the founder and Managing Editor for IIE Transactions on Occupational Ergonomics and Human Factors since 2010. He brought me on as an Editor, early in the process, and I have been very impressed with his passion for the journal, his tireless work to ensure the quality of the manuscripts being evaluated for publication, and his collegiality during my many direct interactions with him regarding the journal. He has created an excellent addition to the ergonomics and human factors literature, and the journal has quickly diversified to include research from all over the world. He has been particularly dedicated to shepherding submissions from researchers in developing countries.

In conclusions, I strongly endorse Dr. Maury Nussbaum's application to become a Fellow of the International Ergonomics Association. I believe he is an ideal candidate for such a distinction. He is an excellent educator, mentor, researcher and administrator, and his combination of breadth of expertise, and commitment to the field, are unsurpassed in our international community. I give him my absolutely strongest recommendation for this honour.

Sincerely

Jim Potvin
Professor

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(905) 525-9140 ext 23004, fax (905) 527-3071

Ford Motor Company
6100 Mercury Drive
Dearborn, MI 48121
International Ergonomic Association,

I would like to recommend Dr Maury Nussbaum to be considered as a Fellow by the International Ergonomics Association. As a global Ergonomic technical expert for Ford Motor Company, I have had the pleasure and benefit of working with Dr Nussbaum. He is the leader in physical ergonomics research in the United States.

The American Automotive Manufacturing Association (AAMA) funded work with Dr Nussbaum to investigate upper extremity risk assessments because of his expertise. Overhead work is common in the assembly plant resulting in shoulder and neck issues. Dr Nussbaum's research contributes to minimize the impact of these types of injuries that we experience

Dr Nussbaum's expertise not only addresses ergonomic analysis and risk assessment but approaches ergonomics holistically. He is published in the area of the effects of age, gender, and obesity on worker capacity. This type of research will influence and impact industry human resource policies of the future. Within the field of Industrial engineering, Dr Nussbaum's work has influenced the effects of work organization, with significant contributions in the area of muscle fatigue, job rotation, influence of prolonged/repetitive trunk flexion.

The automotive sector has long since recognized Dr Nussbaum's contributions including hand/finger force guidelines and factors influencing repetitive strain injury. As such, Dr Nussbaum's reputation has resulted in work in the area of Dynamic impacts for automotive assembly tasks with the United States Council of Automotive Research (USCAR). USCAR is a collaborative automotive technology company whose goal is to further expand the technical knowledge of the US auto industry.

In my role at Ford, I continue to seek relevant and applied research to influence the design and improve the health and safety of our manufacturing environment. Dr Nussbaum's contributions are key to establishing these improvements to our workplace safety and manufacturing business.

Yours Sincerely;

Allison Stephens

Allison Stephens M.Sc, CPE

Technical Leader, Global Ergonomics Manager

TOSHIBA
Leading Innovation >>>

April 24, 2015

To whom it may concern,

It is my honor and privilege to support Dr. Maury Nussbaum in his bid to become an IEA Fellow. Dr. Nussbaum is in expert in Human Factors Engineering & Ergonomics as both a researcher and an educator. I first contacted him in 1999. Then, from January 2000 to September, I worked as a visiting researcher at Virginia Tech under Dr. Nussbaum's supervision. After returning to Japan I used the Applied Ergonomics that I learned from Dr. Nussbaum to design and evaluate consumer electronics products. This allowed me to successfully develop a vacuum cleaner, which was easy to use which had a grip that produced less strain on the operator's arms and shoulders.

From 2002 until 2006 Toshiba and Virginia Tech conducted joint research into the usability and accessibility of cellular phones. Dr. Nussbaum was the lead researcher from Virginia Tech, taking responsibility for the university's portion of the program. A number of findings were obtained as a direct result of his leadership. As a result of this research, Toshiba was able to develop an easy-to-use, easily accessible cellular phone, and this provided a significant contribution to Toshiba's business.

Dr. Nussbaum is not only an excellent researcher, he is also an outstanding leader. There are students enrolled in his research lab from many different countries, many of whom studied under him. Dr. Nussbaum has an international network of contacts having spent so many years as a researcher and educator. For these reasons I believe that Dr. Nussbaum has the qualifications necessary to become an IEA Fellow.

Sincerely,

Kei Tomioka
A Member of Japan Ergonomics Society
Senior Manager, Design Management Department
Design Center, Toshiba Corporation
1-1, Shibaura 1-Chome, Minato-ku,
Tokyo 105-8001 Japan
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April 23, 2015

International Ergonomics Association (IEA)
Fellow Selection Committee

Re: Recommendation for Dr. Maury Nussbaum, Candidate for IEA Fellow

Dear Selection Committee,

It is my pleasure to support the nomination of Dr. Maury Nussbaum for the IEA Fellow Award. I believe that he is exceptionally well qualified for this high honor. The selection criteria for the award include eligibility and distinction. In terms of eligibility, Dr. Nussbaum has held a high service load in affiliated societies for more than 10 years and has an extensive publication record. In terms of distinction, I believe that a strong argument can be made that he has made tremendous contributions to the development of new knowledge in the field of human factors engineering and ergonomics.

I will begin by describing the distinctive contributions that Dr. Nussbaum has made to his field. He is an expert in a wide variety of topics within the broad realm of human factors engineering and ergonomics. Specifically, he has expertise in occupational biomechanics, ergonomics, and safety. He also has strong credentials in the fields of work physiology and muscle fatigue. He works in diverse application areas ranging from human balance and fall risk to aging and obesity. During his 18 years in the Grado Department of Industrial and Systems Engineering at Virginia Tech, he has amassed a record of achievement that is perhaps best labelled 'amazing'. In a letter of recommendation for Dr. Nussbaum's successful bid for the Institute of Industrial Engineers (IIE) Fellow Award in 2014, Dr. Paul Griffin of Penn State University (now at Georgia Tech) called Dr. Nussbaum "…one of the top two human factors faculty in the country." I couldn't agree more with this assessment.

Dr. Nussbaum has been quite adept at earning externally funded research funds to support his research program. He has earned a personal share of external research funds in the amount of approximately $6 million as a part of a larger portfolio of $16 million as a research collaborator. Once the funds are obtained, he is a strong student advisor and mentor, and turns his research efforts into publications of incredible quality and impact. During his time on the Virginia Tech faculty, he has advised more than 20 PhD students to completion of their degrees, while concurrently advising approximately 20 more MSISE students to completion. Eleven of his PhD graduates have earned academic positions, with several of them working in some of the finest engineering programs in the world. Additionally, he has mentored 7 Post-Doctoral Associates and has hosted 7 Visiting Professors from all over the world. Clearly, he is multiplying his level of achievement by extending knowledge to a large cadre of collaborative researchers. Also, he has published a more than 140 journal articles and approximately 150 conference papers or abstracts. His publications have resulted in more than 2,700 citations, an h-index of 30, and an i10-index of 77. These results undoubtedly indicate his impact on technical innovation in his field, yet he has also had an impact on practical innovations. His work on muscle fatigue, for example, has affected industry guidelines for rest schedules in repetitive work situations. His work with driver safety issues with UPS was so impactful that he and his colleagues earned the 2008 Alexander Williams Design Award from the *Human Factors and Ergonomics Society (HFES)*. Dr. Nussbaum is also a Board Certified Professional Ergonomist (BCPE).

Although it is perhaps not directly related to technical achievement in terms of measurable output, it is also very noteworthy that Dr. Nussbaum is an incredibly strong classroom instructor. He routinely earns teaching evaluation scores that place him among the elite teachers in the College of Engineering at Virginia Tech. This indicates that he is not only an extremely well-rounded academician, but that he cares deeply about the students in his charge.

Dr. Nussbaum's eligibility for this award based on a strong service orientation is very clear. Internally at Virginia Tech, Dr. Nussbaum has been a true 'champion' of physical and occupational ergonomics. He has taught multiple courses in this area, has brought faculty members together and has widely collaborated, and has enhanced the visibility of occupational safety and health. Perhaps most noteworthy in this area of achievement is his leadership of the Occupational Safety and Health Research Center (OSHRC), which brought together researchers from multiple on-campus entities to pursue large-scale funded project opportunities.

Externally, he has led or participated in a number of activities directly related to the field of ergonomics. As a Past-President of IIE, I am perhaps most familiar with service contributions to that organization, so I will begin with those. Most significantly in my view, he is the Founding and Managing Editor for one of IIE's newest journals, the *IIE Transactions on Occupational Ergonomics and Human Factors*. In this role, he generated the journal proposal for the IIE Board of Trustees and to the publisher and had a significant uphill battle to get the journal initiated. He specified the journal's aims and scope, developed the author instructions, guidelines, and templates, and recruited Associate Editors, an Editorial Board and an Advisory Panel. He takes a 'hands on' approach as Managing Editor and works very hard to maintain a high quality journal in which IIE can take great pride. He has also worked very hard to recruit top authors to write papers for the journal.

Dr. Nussbaum has also been very active in the *Applied Ergonomics* Conference. Specifically, he has served as a member of the Program Committee for two years and he successfully solicited papers, reviewed submissions, and developed sessions. He was also a Human Factors and Ergonomics Track Chair for the *Industrial Engineering Research Conference* (*IERC*, now *ISERC*) in 2009. By participating in these conferences, and by editing IIE's new journal, Dr. Nussbaum had a goal to better reengage human factors and ergonomics faculty members by offering additional high-quality content through IIE. I believe that his efforts have been successful and that he has made a strong impact on his research community through his service.

In addition to his participation in IIE, he is also active in the American Industrial Hygiene Association, the Human Factors and Ergonomics Society, the International Society of Occupational Ergonomics and Safety, the American Society of Biomechanics, The Institute for

Ergonomics and Human Factors, and the International Society of Biomechanics. He has served as an Editorial Board Member on five strong journals; *Ergonomics*, the *Journal of Occupational and Environmental Hygiene*, the *Journal of Applied Biomechanics*, the *American Industrial Hygiene Journal*, and *Applied Ergonomics*. He is a Consulting Editor for the *Journal of Biomechanics*. He is already a Fellow of the Institute of Ergonomics and Human Factors, and is also a fellow of the American Industrial Hygiene Association. I urge you to strongly consider him for the high honor of IEA Fellow. Thank you very much for considering my strong support for Dr. Nussbaum for this award.

Sincerely,

Dr. G. Don Taylor, Jr.
Charles O. Gordon Professor and Department Head

MAURY A. NUSSBAUM, Ph.D., CPE

(Resume as of April, 2015)

Dept. of Industrial and Systems Engineering
Virginia Tech
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EDUCATION:

Ph.D. Industrial and Operations Engineering, April 1994
The University of Michigan, Ann Arbor

M.S. Bioengineering, May 1989
The University of Michigan, Ann Arbor

B.S.E. Mechanical Engineering, May 1988
The University of Michigan, Ann Arbor

B.S. Biomedical Sciences, May 1985
The University of Michigan, Ann Arbor

ACADEMIC APPOINTMENTS:

Assistant Department Head and Graduate Program Director — *Aug 2014 - present*
H.G. Prillaman Professor — *Aug 2011 - present*
H.G. Prillaman Professor Fellow — *Aug 2008 – Aug 2011*
Professor — *June 2007 – Aug 2011*
Associate Professor — *June 2002 – June 2007*
Assistant Professor — *August 1996 – June 2002*
Department of Industrial and Systems Engineering
Virginia Tech

Director — *January 2011 – present*
VT Occupational Safety and Health Research Center (OSHRC)

Affiliate Faculty Member — *May 2006 – present*
Myers-Lawson School of Construction

Affiliate Professor
VT Department of Mechanical Engineering — *June 2005 – present*
VT Department of Engineering Science and Mechanics — *October 2013 – present*

Faculty Affiliate — *January 2004 – present*
VT Center for Gerontology

Core Faculty Member — *August 2003 – present*
VT/Wake Forest School of Biomedical Engineering and Sciences

Post-Doctoral Research Fellow — *May 1994 - August 1996*

Center for Ergonomics
The University of Michigan, Ann Arbor

Adjunct Assistant Professor — *September 1995 - April 1996*
Industrial and Operations Engineering
The University of Michigan, Ann Arbor

Research Assistant — *August 1989 - May 1994*
Center for Ergonomics
The University of Michigan, Ann Arbor

OTHER APPOINTMENTS:

Visiting Professor
Mechanical Engineering — April 23-May 5, 2012
University of Cagliari, Cagliari, Italy

School of Biological Science and Medical Engineering — April 5-12, 2013
Beihang University, Beijing, China

RESEARCH and TEACHING INTERESTS:

Occupational Ergonomics & Injury Prevention
Measuring and Modeling Balance & Postural Control
Ambulatory Ergonomics Exposure Assessment
Individual Differences in Work Capacity & Injury Risks
Ergonomic Design & Evaluation Guidelines
Basic & Applied Biomechanics
Work Physiology & Muscle Fatigue
Consumer Product Design & Evaluation
Slip, Trip & Fall Prevention

HONORS and AWARDS:

Outstanding Achievement Award for Graduate Student, Industrial and Operations Engineering Department, University of Michigan (1993)
The University of Michigan Rackham Predoctoral Fellowship (1993 – 1994)
American Society of Biomechanics-Young Investigator Award (1993)
Professor of the Year (2002, 2007) VT HFES Student Chapter
Best Lecturer of the Year (2003, 2004, 2007) VT HFES Student Chapter
Faculty Fellow (2004 – 2006) VT College of Engineering
Alexander Williams Design Award, Human Factors and Ergonomics Society (September, 2008). Award given for “UPS Driver Safety Project” to a research team led by Dr. Smith-Jackson and comprised of eight VT faculty and four UPS employees.
Dean’s Award for Excellence in Research (2009) VT College of Engineering
Best Paper Award (2009) IERC Human Factors and Ergonomics Track (co-author, along with three students and one faculty).

Fellow (2009) Institute of Ergonomics and Human Factors (formerly The Ergonomics Society)
Fellow (2013) American Industrial Hygiene Association (FAIHA™)
Fellow (2014) Institute of Industrial Engineers

PROFESSIONAL MEMBERSHIPS (status)(initial membership):
American Industrial Hygiene Association (Fellow) (1996)
American Society of Biomechanics (1992)
Institute of Ergonomics and Human Factors (Fellow) (1994)
Human Factors and Ergonomics Society (Full Member) (1994)
Institute of Industrial Engineers (Fellow) (1993)
International Society for Occupational Ergonomics and Safety (Full Member) (1995)
International Society of Biomechanics (1996)
Sigma Xi (1994)

FUNDED RESEARCH PROJECTS and GRANTS:
Value of total external sponsored research to date: $16.32M
Amount for which directly responsible: $5.89M (36%)

1. "Enhancing safety when using head-worn display technologies in warehousing", Center for Engineering Logistics and Distribution (CELDi), 08/10/15 – 08/09/16, $76,336. PI: M.A. Nussbaum, co-Is: S. Kim and J. Gabbard. Responsibility = 38%.
2. "Developing dynamic force limits", USCAR, 01/01/15 – 12/31/15, $75,000. PI: M.A Nussbaum, co-Is: S. Kim and M.J. Agnew. Responsibility = 65%.
3. "Understanding the safety and health of loggers in mechanized harvesting operations", Johns Hopkins University, NIOSH ERC Pilot Program, 07/01/14-06/30/15, $7,884. PI: S. Kim, co-I: M.A. Nussbaum. Responsibility = 20%.
4. "Trunk postural control in service members with lower-extremity trauma", DoD, 01/01/15 – 12/31/17, $74,149. PI: M.A. Nussbaum. Responsibility = 100%. Subcontract from Walter Reed National Military Medical Center (B. Hendershot, PI).
5. "Balance recovery training for fall prevention in retirement communities". NIH/NIA, 09/01/14 – 05/31/16, $78,313, PI: M.A. Nussbaum (responsibility = 32%), co-I: P. Estabrooks. Subcontract from Texas A&M University (PI: M. Madigan). R21 AG045723.
6. "Investigating the impact of ergonomic injury risk on productivity and quality". The Boeing Company, 02/26/14 – 04/30/15, $50,998, PI: M.J. Agnew, Co-I: M.A. Nussbaum (responsibility = 30%).
7. "Effects of pesticide exposure on postural control." NIEHS, 03/01/13 – 02/28/16, $246,164. PI: M.A. Nussbaum (responsibility = 80%), Co-I: M.L. Madigan. Subcontract from WFU School of Medicine (T. Arcury, PI): CBPR on pesticide exposure & neurological outcomes for Latinos: PACE4. 3R01 ES008739-16S1.
8. "Aging, neuromuscular behavior, and risk of occupational low back pain". NIOSH, 07/01/12 – 06/30/15 (1-yr NCE), $71,937, PI: M.A. Nussbaum. Subcontract from U Kentucky (B. Bazrgari, PI). R21 OH010195.
9. "Ergonomic research on manufacturing tasks", Equipois, Inc. ($29,994; 06/11/12 – 05/31/13). PI: Nussbaum, Co-I: M. Agnew (responsibility – 70%).
10. "Effects of obesity and age on balance and fall risk – Implications for safety guidelines". NIOSH. ($787,430; 09/01/11 – 08/31/15). PI: Madigan, Co-Is: Nussbaum, Agnew, and Hindman (responsibility – 20%). R01 OH009880.
11. "Safety and Ergonomics Training". NIOSH. ($460,428; 07/01/11 – 6/30/16). PI: M.A. Nussbaum, Co-Is: M. Agnew, J. Casali, B. Kleiner, T. Lockhart, T. Smith-Jackson, W. Winchester, and D. Young (responsibility – 41%). 2T03 OH008613.
12. "Agriculture, forestry, and fisheries in the Southeast: Immigrant worker health". NIOSH. ($30,000; 04/01/10 – 03/31/11) PI: T. Arcury, Co-Is: M. Agnew, J. Grzywacz, T. Howard, B. Klein, M.A. Nussbaum (10%), S. Quandt, and Q. Vallejos. R13 OH009744.

13. “Decision support system for ergonomic construction design: Phase II”, NIOSH. ($2,162,773; 09/01/09-08/31/14) PI: M.A. Nussbaum, co-Is: J.P. Shewchuk and M.J. Agnew (responsibility – 45%). U60 OH009761.
14. “Effects of localized muscle fatigue on risk of occupational slips and falls”, NIOSH. ($1,184,470; 09/01/09-08/31/14) PI: T.E. Lockhart, co-I: M.A. Nussbaum (responsibility – 20%). R01 OH009222.
15. “Accessible smart phone design: user requirements capture and formative evaluation”, Toshiba Corporation, Japan. ($34,937; 01/12/09-05/09/09) PI: T.L. Smith-Jackson, co-I: M.A. Nussbaum (responsibility – 30%).
16. “Evaluation of patient handling devices”. Stryker Medical. ($23,436; 11/01/07-08/01/08) PI: M.A. Nussbaum, co-I: M.J. Agnew (responsibility – 50%).
17. “Investigating joist buckling as a cause of falls from elevation”. NIOSH. ($388,640; 08/01/07-07/31/10) PI: D. Hindman, co-I: M.A. Nussbaum (responsibility – 10%). R21 OH009802.
18. “Workplace factors & gender in dynamic spinal stability”, NIAMS. ($741,684; 03/01/07-02/28/11) PI: K.P. Granata (responsibility – 0%). *as of April 16, 2007: PI: M.L. Madigan, co-PI: M.A. Nussbaum (responsibility – 40%). 2R01 AR046111.
19. “Evaluation of engineering control technology for drywall sanding operations”, Johns Hopkins University NIOSH Education and Research Center. ($7,500; 07/01/06-06/30/08). PI: M.A. Nussbaum (responsibility – 100%).
20. “Evaluation of patient handling devices”, Stryker Medical. ($30,755; 12/01/06-08/09/08). PI: M.A. Nussbaum; co-PI: M.J. Agnew (responsibility – 50%).
21. “Occupational Safety and Health Training Grant”. NIOSH. ($344,340; 07/01/06-6/30/11). PI: M.A. Nussbaum, Co-Is: M. Agnew, J. Casali, B. Kleiner, T. Lockhart, T. Smith-Jackson, W. Winchester (responsibility – 55%). T01 OH008613.
22. “Occupational Trunk Flexion and Neuromuscular Disturbance”, NIOSH. ($1,311,501; 08/01/06-07/31/11). PI: K. Granata, co-PI: M.A. Nussbaum (responsibility – 15%). *as of April 16, 2007: PI: M.A. Nussbaum, co-PI: M.L. Madigan. (responsibility – 60%). R01 OH008504.
23. “DSP Safety Training System”, United Parcel Service. ($450,000: 06/08/06-11/01/07). Contract PI: K.L. Babski-Reeves; VT-PI: T. Smith-Jackson; Co-Is: J. Casali, B. Kleiner, J. Lancaster, T. Lockhart, M. Nussbaum, W. Winchester. (responsibility – 11%).
24. “HMC-Virginia Tech Research Partnership”, Hyundai Motor Company, Korea. ($109,976: 10/01/05 – 09/30/06). PI: M.A. Nussbaum, Co-PI: K.L. Babski-Reeves. (responsibility – 80%).
25. “Needs Analysis and Requirements Acquisition for Inclusive Design of Cell Phones: United Kingdom and Germany”, Toshiba Corporation, Japan. ($58,461: 05/08/05-11/15/05). PI: T.L. Smith-Jackson, co-PI: M.A. Nussbaum. (responsibility – 40%).
26. “Center for Innovation in Construction Safety and Health: A Socio-Technical Systems Integrated Approach to Safety and Health”, NIOSH/NIH, (Total funding, $3,447,166: 09/15/04 – 09/14/09) PI: B.M. Kleiner. [Subprojects: Center for Innovation in Construction Safety and Health (co-PI) $137,357 or 14%; Decision Support Tool for Ergonomic Construction Design [simulation] Nussbaum (PI) $444,484 (25% Yr1, 35% Yr2, 45% Yr3, 50% Yrs 4-5)]. U19 OH008308.
27. “Muscle strength and age effects in balance recovery”, NIOSH, ($139,844: 08/01/04 – 07/31/07). PI: M.L. Madigan; Co-PI: M.A. Nussbaum. (responsibility – 20%). R03 OH007821.
28. “Identification of physically demanding patient handling tasks in an acute care hospital”, Johns Hopkins University NIOSH Education and Research Center, ($15,000: 07/01/04 – 06/30/06). PI: M.A. Nussbaum. (responsibility – 100%).

29. “Design, testing, and verification of the cellular phone navigation system”, Toshiba Corporation, Japan, ($59,533, 03/23/04 – 03/24/05). PI: T.L. Smith-Jackson; M.A. Nussbaum, co-PI. (responsibility – 40%).
30. “VT Post Baccalaureate research and education program”, DHHS 1R25 DM066534; ($1,955,743, 6/1/03 — 5/31/08). PI: E. Smith. (responsibility – 0%).
31. “Risk factors and controls for falls from heights”, NIOSH R01 OH007882 ($914,286, 9/1/03 – 8/31/08). PI: M.A. Nussbaum, co-PI: M.L. Madigan. (responsibility – 60%).
32. “Recommended limits for manual torquing tasks”, Honda of America, Mfg. Inc., ($120,405, 1/1/03 – 5/31/04). PI: K.L. Babski-Reeves, co-PI: M.A. Nussbaum. (responsibility – 50%).
33. “Usability inspection, testing, and evaluation of cell phone user interfaces”, Toshiba Corporation, Japan, ($44,410, 10/16/02 – 08/15/03). PI: T.L. Smith-Jackson; M.A. Nussbaum, co-PI. (responsibility – 50%).
34. “Support for research on patient handling”, US Army Center for Health Promotion and Preventive Medicine, Ergonomics Program, ($10,000, 06/01/02 – 05/30/06). PI: M.A. Nussbaum. (responsibility – 100%).
35. “Development of a subjective workload assessment tool for situations requiring physical and mental demands”, Army Research Lab – Human Research and Engineering Directorate, (50,511, 1/1/02 – 12/31/02). PI: M.A. Nussbaum. (responsibility – 100%).
36. “Determination of cart kinematics during pushing and pulling tasks”, Honda of America, Mfg. Inc., ($3,335, 9/1/01 – 10/1/01). PI: M.A. Nussbaum; co-I: T. Lockhart. (responsibility – 50%).
37. “Performance and usability evaluation of cellular phones for persons with disabilities”, Toshiba Corp. ($25,325, 8/1/01 – 5/31/02). PI: M.A. Nussbaum, Co-PI: T.L. Smith-Jackson. (responsibility – 50%).
38. “Critical incident research on laptop computers”, Toshiba Corp. ($26,828, 8/1/01 – 5/31/02). PI: M.A. Nussbaum, Co-PI: T.L. Smith-Jackson. (responsibility – 50%).
39. “Recommended limits for overhead work tasks”, Honda of America, Mfg. Inc., ($94,555, 6/1/01 – 5/15/02). PI: M. Nussbaum. (responsibility – 100%).
40. "Evaluation of the USPS DEAT process", United States Postal Service, ($11,554, 5/1/01 – 7/1/01). PI: M.A. Nussbaum. (responsibility – 100%).
41. "Survey on technology needs for disabled persons", Toshiba Corp., ($12,591, 2/28/01 – 6/30/01). PI: M.A. Nussbaum; Co-PI: T.L. Smith-Jackson. (responsibility – 50%).
42. "Evaluation of existing assessment tools during combined mental and physical workload", Army Research Lab – Human Research and Engineering Directorate, ($50,919, 10/1/00 – 11/30/01). PI: M.A. Nussbaum. (responsibility – 100%).
43. "Aging effects on intermittent work capacity", NIOSH R01 OH04089 ($418,740, 9/30/00 – 9/29/04). PI: M.A. Nussbaum; Co-PI: L.A. Wojcik. (responsibility – 95%).
44. "Occupational safety and health training grant", NIOSH ($281,434, 07/01/01 – 06/30/06). PI: M.A. Nussbaum; Co-PIs: T. Smith-Jackson, K. Babski-Reeves, J.G. Casali, T. Lockhart, D. Young. (responsibility – 40%).
45. "Hand force limits for manual insertion tasks", Honda of America Mfg., Inc. ($79,913, 3/31/00 – 12/31/00). PI: M.A. Nussbaum. (responsibility – 100%)
46. “Literature search and research on use of psychophysical ratings as measures of physical and mental workloads”, Army Research Laboratory – Human Research and Engineering Directorate, ($50,572, 8/11/99 – 9/30/00). PI: M.A. Nussbaum. (responsibility – 100%)
47. “Cost engineering and industrial/systems engineering support for the Navy CVX Program”, NSWC/Dahlgren ($350,000, 2/17/98-5/1/98). PI: K. Triantis. (responsibility – 20%).
48. “Quantifying time-to-fatigue during short cycle overhead work operations”, American Automobile Manufacturers Association, ($109,309, 1/15/98 – 12/31/98). PI: M.A. Nussbaum (responsibility – 100%).

49. “Master of Science: ISE Safety Engineering”, NIOSH/PHS ($202,326, 7/1/96 – 6/30/01). PI: T.A. Dingus; Co-PIs: J.G. Casali, M.A. Nussbaum. (responsibility – 33%).

COURSES TAUGHT:

ISE 3624–Industrial Ergonomics: Undergraduate course that provides an introduction to major aspects of physical ergonomics, human performance, safety, and applications in industrial work design.

ISE 5024–ISE Seminar: Introduction to Industrial and Systems Engineering. Two-hour seminar, consisting of guest lectures from the department and the university and a formal lecture hour covering major topics within ISE.

ISE 5614–Human Physical Capabilities: Graduate course that provides an overview of occupational biomechanics, work physiology, and physical job task analysis.

ISE 5615–Human Factors Research Design I: Graduate course covering procedures for conducting human factors and ergonomics experiments, including design alternatives, statistical models, and analysis.

ISE 5616–Human Factors Research Design II: Graduate course covering advanced experimental designs and statistical models relevant to human factors and ergonomics research.

ISE 6014–Proposing Industrial Engineering Research: Advanced graduate course designed to provide students with a better understanding of the processes involved with proposing research in Industrial and Systems Engineering, and to improve their abilities to generate such proposals.

ISE 6624–Advanced Methods in Occupational Biomechanics: Advanced graduate course on current topics in occupational biomechanics and physical ergonomics.

Short Courses:

“Ergonomics and Occupational Biomechanics: An Introduction”. Department of Mechanical Engineering, University of Cagliari, Italy. (10 hours, April 23 – May 4, 2012)

Record of Teaching Effectiveness

Response to evaluation question = "Overall rating of this instructor":

Semester	*Course Number*	*Excel.*	*Good*	*Fair*	*Poor*	*Total Respon.*	*Total Enrolled*	*Mean (4-point scale)*
Fall 1996	ISE 3624	1	13	7	1	22	28	2.64
Spr 1997	ISE 3624	27	31	0	0	58	70	3.47
Fall 1997	ISE 5614	8	6	1	0	15	17	3.47
Spr 1998	ISE 3624	15	22	1	0	38	45	3.37
Fall 1998	ISE 3624	10	17	0	0	27	36	3.37
	ISE 5024	15	19	4	0	38	44	3.29
Spr 1999	ISE 3624	19	39	2	0	60	75	3.28
	ISE 5614	10	0	0	0	10	10	4.00
Fall 1999	ISE 5615	3	9	0	0	12	13	3.25
Spr 2000	ISE 3624	7	6	1	0	14	17	3.43
	ISE 5614	4	6	0	0	10	11	3.40
Fall 2000	ISE 3624	11	16	1	0	28	36	3.36
Spr 2001	ISE 3624	16	27	4	0	47	57	3.26
	ISE 5614	16	2	2	0	20	20	3.70
Fall 2001	ISE 3624	6	16	6	0	28	49	3.00
Spr 2002	ISE 5614	17	3	1	0	21	24	3.76
Fall 2002	ISE 3624	12	15	4	1	32	40	3.19
Spr 2003	ISE 3624	44	15	0	0	59	73	3.75
	ISE 5614	8	5	0	0	13	14	3.62
Fall 2003	ISE 5615	8	1	0	0	9	10	3.89
Spr 2004	ISE 5614	12	2	0	0	14	13	3.86
Fall 2004	ISE 5614	11	3	1	0	15	21	3.67
	ISE 5615	18	1	1	1	21	25	3.71
Spr 2005	Leave							
Fall 2005	ISE 5614	14	4	0	0	18	18	3.78
Spr 2006	ISE 6624	8	2	0	0	10	10	3.80
Fall 2006	ISE 5614	9	1	0	0	11	14	3.91
Spr 2007	ISE 5615	N/A	N/A	N/A	N/A	N/A	N/A	
Fall 2007	ISE 5614	16	2	0	0	18	19	3.89
Spr 2008	ISE 5616	5	0	0	0	5	6	4.00
Fall 2008	ISE 5614	10	3	0	0	13	13	3.77
Spr 2009	ISE 5615	8	0	0	0	8	9	4.00
Fall 2009	ISE 6984	15	1	0	0	16	17	3.94
Spr 2010	ISE 5615	10	1	2	1	14	14	3.43
Fall 2010	ISE 5614	13	2	0	0	15	15	3.87
Spr 2011	ISE 5615	9	9	0	0	18	20	3.50
Totals:		416	299	38	4	757	891	**3.49**
(%)		55	39	5	1	85		
UGrad		168	217	26	2	413	517	**3.33**
Graduate		248	82	12	2	311	340	**3.67**

Response to evaluation question = "Overall, the instructor's teaching was effective":

Semester	*Course Number*	*Strongly Agree*	*Agree*	*Somewhat Agree*	*Somewhat Disagree*	*Disagree*	*Strongly Disagree*	*# of Responses*	*# Enrolled*	*Mean (6-point scale)*
Fall 2011	ISE 6984	4	2	0	0	0	0	6	6	5.67
Fall 2012	ISE 5614	7	3	2	0	1	1	14	15	4.86
Fall 2013	ISE 6014	4	1	0	0	0	0	5	10	5.80
Totals:		15	6	2	0	1	1	25	31	**5.24**
(%)		60	24	8	0	4	4	85		
UGrad		-	-	-	-	-	-	-		
Graduate		15	6	2	0	1	1	20	21	**5.24**

ADVISING of CURRENT and FORMER STUDENTS:
(Current or last known positions are listed)

Ph.D Dissertations, Directed

1. Angela DiDomenico (2003) "An investigation on subjective assessments of workload and postural stability under conditions of joint mental and physical demands." Human Factors / Biomechanics Expert, *ARCCA Incorporated*, Penns Park, PA.
2. Hardianto Iridiastadi (2003) "Localized muscle fatigue during isotonic and nonisotonic isometric efforts." Associate Professor, Department of Industrial Engineering, *Bandung Institute of Technology*, Bandung, Indonesia.
3. Miguel Perez (2005) "Prediction of whole-body lifting kinematics using artificial neural networks." Director, Center for Data Reduction and Analysis Support, *Virginia Tech Transportation Institute*, Blacksburg, VA.
4. Yassierli (2005) "Muscle fatigue during isometric and dynamic efforts in shoulder abduction and torso extension: age effects and alternative electromyographic measures." Associate Professor, Department of Industrial Engineering, *Bandung Institute of Technology*, Bandung, Indonesia.
5. Laura Hughes Ikuma (2007, co-advisor with K. Babski-Reeves) "The influence of multiple risk factors on WMSD risk and evaluation of measurement methods used to assess risks." Associate Professor, Mechanical & Industrial Engineering Department, *Louisiana State University*, Baton Rouge, LA.
6. Shane McLaughlin (2007, co-advisor with T. Dingus) "Analytic assessment of collision avoidance systems and driver dynamic performance in rear-end crashes and near-crashes." Research Scientist, Center for Automotive Safety Research, *Virginia Tech Transportation Institute*, Blacksburg, VA.
7. Deb Dickerson (née Young) (2007) "Evaluation of dust control technologies for drywall finishing operations: industry implementation trends, worker perceptions, effectiveness and usability." Assistant Professor, School of Construction, *Virginia Tech*, Blacksburg, VA.
8. Martin Tanaka (2008, SBES, co-advisor with S. Ross) "Biodynamic analysis of human torso stability using finite time Lyapunov exponents." Assistant Professor, Department of Engineering and Technology, *Western Carolina University*, Cullowhee, NC.
9. Xingda Qu (2008) "Development and evaluation of postural control models for lifting motions and balance control." Professor, College of Mechatronics and Control Engineering, *Shenzhen University*, Shenzhen, China.

10. Gyouhyung Kyung (2008) “An integrated human factors approach to design and evaluation of the driver workspace and interface: driver perceptions, behaviors, and objective measures.” Associate Professor, Department of Human & System Engineering, *Ulsan National Institute of Science and Technology (UNIST)*, South Korea.
11. Myrna Callison (2009) “Identification, evaluation and control of physically demanding patient-handling tasks in an acute care facility.” Ergonomics Program Manager, *US Army CHPPM* & Chair, DOD Ergonomics Working Group, Aberdeen Proving Ground, MD.
12. Linsey Steege (née Barker) (2009) “Measuring and modeling the effects of fatigue on performance: specific application to the nursing profession.” Assistant Professor, School of Nursing, *University of Wisconsin*, Madison, WI.
13. Dingding Lin (2010) “Effects of localized muscle fatigue on postural control: interactive effects with inclined surfaces and unexpected loads, and intervention efficacy.” Research Staff Member, *IBM China Research Laboratory*, Beijing, China.
14. Leanna Reardon (née Horton) (2012, co-advisor with M. Agnew) “The effects of job rotation parameters on localized muscle fatigue and performance: an investigation of rotation frequency and task order.” Industrial Engineer, *Michelin*, Greenville, SC.
15. Lora Cavuoto (2012) “Evaluating obesity-related differences in upper extremity and trunk muscular capacity.” Assistant Professor, Department of Industrial & Systems Engineering, *University at Buffalo*, Buffalo, NY.
16. Bradford Hendershot (SBES, 2012) “Alterations and asymmetries in trunk mechanics and neuromuscular control among persons with lower-limb amputation: exploring potential pathways of low back pain.” Research Biomechanist, Center for Performance and Clinical Research, DOD-VA Extremity Trauma and Amputation Center for Excellence, *Walter Reed National Military Medical Center*, Baltimore, MD.
17. Sunwook Kim (2012) “Development and evaluation of methods to assess physical exposures in the workplace using wearable technologies.” Research Scientist, Department of Industrial and Systems Engineering, *Virginia Tech*, Blacksburg, VA.
18. Jung Yong Lee (2012) “Quantifying the effects of experience on motor behaviors during simulated occupational tasks.” Senior Research Engineer, Ergonomics Technology Team, Research & Development Division, *Hyundai Motor Company*, Seoul, South Korea.
19. Hongbo Zhang (co-advisor with M. Agnew, 2013) “Developing and evaluating new methods for assessing postural control and dynamics.” Research Staff, Department of RecSports, *Virginia Tech*, Blacksburg, VA.
20. Nima Toosizadeh (2013) ”Time-dependent assessment of the human lumbar spine in response to flexion exposures: *in vivo* measurement and modeling.” Research Associate, Department of Surgery, *University of Arizona*, Tucson, AZ.
21. Bochen Jia (2013) “Influence of prolonged sitting and psychosocial stress on lumbar spine kinematics, kinetics, discomfort, and muscle fatigue.” Assistant Professor, Department of Industrial and Manufacturing Systems Engineering, *University of Michigan – Dearborn*, Dearborn, MI.
22. Courtney A. Webster (née Haynes) (SBES, 2013) “Effects of running speed, fatigue, and bracing on motor control of chronically unstable ankles.” Biomechanics Post-Doc, HRED *Army Research Lab*, Aberdeen Proving Ground, MD.
23. Khoirul Muslim (2013) “Traditional posterior load carriage: ergonomic assessment intervention efficacy.” Assistant Professor, Department of Industrial Engineering, *Bandung Institute of Technology*, Bandung, Indonesia.
24. Marc Christian (2014) “Biomarkers of physiological damage and their potential for work-related musculoskeletal disorder risk assessment.” Industrial Engineer, *JFAssociates, Inc.*, Vienna, VA.
25. Xuefang Wu (co-advisor with M. Madigan, 2015) “Toward understanding factors affecting falls among individuals who are obese.”

26. Ehsan Rashedi (degree expected 2015) "Theoretical modeling and validation of a human muscle fatigue model."
27. Peter Fino (ME, co-advisor with G. Brolinson, degree expected 2015) "The effects of mild traumatic brain injury on turning biomechanics and non-linear gait measures in collegiate athletes."
28. Hoda Koushyar (ESM, co-advisor with M. Madigan, degree expected 2015) "Effects of obesity and age on muscle strength, gait, and balance recovery."
29. Christina Garman (ESM, co-advisor with M. Madigan, degree expected 2015) "Understanding the effects of obesity and age on likelihood of tripping and subsequent balance recovery."
30. Alireza Sedighi (degree expected 2016)
31. Saad Alabdulkarim (degree expected 2017)
32. Iman Mokhlespour (degree expected 2017)
33. Kristine Cantin (degree expected 2018)

Ph.D. Dissertations, committee member

1. Zenyuan Wang (EE, 2000) "Artificial intelligence applications in the diagnosis of power transformer incipient faults."
2. Faith McCreary (ISE, 2001) "Empirical evaluation of a constructivist, technology-rich learning environment."
3. Paige Smith (ISE, 2004) "Tools to improve the process of engineering design: an analysis of team configuration and project support."
4. Young Sam Ryu (ISE, 2005) "Development of usability questionnaire models for electronic mobile products using the analytic hierarchy process."
5. Miranda Capra (ISE, 2006) "Usability problem description and the evaluator effect in usability testing."
6. Young Seok Lee (ISE, 2007) "Older adults' user experiences with mobile phones: identification of user clusters and user requirements."
7. Bradley Davidson (BME, 2007) "Experimental and simulation-based assessment of the human postural response to sagittal plane perturbations with localized muscle fatigue and aging."
8. Zachary Doerzaph (ISE, 2007) "Development of a threat assessment algorithm for intersection collision avoidance systems."
9. Shiyong Liu (ISE, 2007) "Three essays on travel demand management strategies for traffic congestion mitigation."
10. Gregory Slota (BME, 2008) "Effects of seated whole-body vibration on spinal stability control."
11. Kathleen Bieryla (ME, 2008) "An investigation of perturbation-based balance training as a fall prevention intervention for older adults."
12. Dennis E. Anderson (ESM, 2010) "An examination of age-related differences in lower extremity joint torques and strains in the proximal femur during gait."
13. Cheng Guo (2010) "Panel stacking and worker assignment problems in residential construction using prefabricated panels: a lean approach."
14. Elizabet Haro (2010) "An evaluation of perceived and observed safety and productivity in residential construction."
15. Ranjana Mehta (2011) "Interactive effects of physical and mental workload: a study of muscle function, capacity and exertion type."
16. Sara Matrangola (ESM, 2011) "An experimental and simulation based approach toward understanding the effects of obesity on balance recovery from a postural perturbation."
17. Emily Miller (ESM, 2012) "Exercise-induced low back pain and neuromuscular control of the spine: experimentation and simulation."

18. José Maria Villaseñor Aguilar (Wood Science, 2012) "Lateral-torsional buckling instability caused by individuals walking on work composite I-joists."
19. Kyunghui Oh (2013) "Use of reading strategy to assess reading medium effectiveness: application to determining the effects of reading medium and generation in an active reading task."
20. Na Mi (2014) "Extended situation awareness theory for mobile augmented reality interfaces to support navigation."
21. Ralph H. Cullen (2014) Multimodal multitasking: the combined effects of postural and cognitive demands on overall workload."

Master Theses, Directed

1. Noris Torres (1998) "Effects of training in modifying work methods and behaviors during common patient handling activities." Vice President and Health Systems Engineer, *CIRACET Corp.*, Ponce, Puerto Rico.
2. Margaret Kirst Lanza (1999) "Effects of tool weight on fatigue and performance during short cycle overhead work operations." Director of Operations and Engineering, *Bosch*, Charleston, SC.
3. Miguel Perez (1999) "Empirical validation of models used to predict torso muscle recruitment." Director, Center for Data Reduction and Analysis Support, *Virginia Tech Transportation Institute*, Blacksburg, VA.
4. Angela DiDomenico Astin (1999) "Finger force capability: measurement and prediction using anthropometric and myoelectric measures." Human Factors / Biomechanics Expert, *ARCCA Incorporated*, Penns Park, PA
5. Andrew Lang (2000) "The correlation between biomechanical loads and psychophysical ratings." Principal Human Factors Engineer, *Bombardier Transportation*, Pittsburgh, PA.
6. Greg Edwards (2000: Co-chair W. Barfield) "Performance and usability of force feedback and auditory substitutions in a virtual environment manipulation task." Human Factors Engineer, *AT&T Labs*, Austin, TX.
7. Hope Johnson (2001) "Strength capabilities and subjective limits for repetitive manual tasks." Human Factors Engineer, *US Consumer Product Safety Commission*, Rockville, MD.
8. Aaron Mooney (2002: Co-chair T.L. Smith-Jackson) "Usability evaluation of notebook computers and cellular telephones among users with visual and upper extremity disabilities." Usability Analyst, *SAS*, Raleigh, NC.
9. Kim Sherman (2003) "An evaluation of fatigue and performance changes during intermittent overhead work." Process Improvement Engineer, *Novo Nordisk*, Raleigh-Durham, NC.
10. Kris Hager (2003) "Reliability of fatigue measures in an overhead work task: A study of shoulder muscle electromyography and perceived discomfort." Associate Director, Hepatitis C Marketing, *Bristol-Myers Squibb*, New York, NY.
11. Deepti Sood (2004) "Predicting shoulder fatigue for long durations using psychophysical measures obtained from short trials." Senior Process Engineering, *Global Foundries*, Hopewell Junction, NY.
12. Andrea Krausman (2004) "Effects of chemical protective clothing on task performance using wearable input devices." Research Psychologist, *U.S. Army Research Lab*, Aberdeen Proving Ground, MD and Doctoral Student, VT.
13. Dong Jae Shin (co-Chair K.L. Babski-Reeves; 2005) "Performance and usability of flexible membrane keyboards."
14. Navrag Singh (2005) "Evaluation of circumferential ankle pressure as an ergonomic intervention to maintain balance perturbed by localized muscular fatigue of the ankle joint." Head of Neuromuscular Control of Movement Group, Institute of Biomechanics, *Swiss Federal Institute of Technology*, Zurich, Switzerland.

15. Renate Van Zandwijk (Vrije Universiteit, Amsterdam; 2006) “Reliability of COP- and COM-based measures and relative sensitivity to induced localized muscle fatigue.” Doctoral Student, *University of Texas*.
16. Hongbo Zhang (2006) “Use of statistical mechanics methods to assess the effects of localized muscle fatigue on stability during upright stance.” Research Staff, Department of RecSports, *Virginia Tech*, Blacksburg, VA.
17. Ravi Kant (co-chair K.L. Babski-Reeves; 2007) “Effect of work exposure on maximum acceptable repetition rates in a manual torquing task.” Senior Business Analyst, *IGATE*, Mumbai, India.
18. Robin Littlejohn (co-chair K.L. Babski-Reeves; 2008) “Thermographic assessment of the forearm during data entry tasks: a reliability study.” Doctoral Student, *Mississippi State*.
19. Steven Voinier (ME, co-chair M.J. Agnew; 2015) “Passive stiffness characteristics of the scoliotic lumbar torso in trunk flexion, extension, lateral bending, and axial rotation.” Mechanical Engineer, *KBR, Inc*.

Master Theses, committee member

1. Jae Kim (1998) “The effects of frequency of interaction and quality of interaction in a web-based learning system.”
2. Kevin Baird (1999) “Evaluating the effectiveness of augmented reality and wearable computing for a manufacturing assembly task.”
3. Traci Thomas (1999) “Evaluation of training technique as a means of influencing safety knowledge, risk perception and proper respirator donning ability among respiratory protection users.”
4. Jason Saleem (1999) “Quantifying the effects of training and a work analysis tool on participatory ergonomics performances.”
5. Eric Nash (2000) “The effects of icon usage and communication style on mental workload using wearable computers.”
6. Ron Spencer (2000) “Analysis of performance as a function of hand-held input control devices and visual displays.”
7. Jennifer Stanfield (2001) “Identification and quantification of video display workstation set up on risk factors associated with the development of low back and neck discomfort.”
8. Mitchell A. Woods (2002) “Effects of negatively sloped keyboard wedges on user performance and perceptions.”
9. Stephanie Binder (2003) “Evaluation of discomfort glare and pavement marking material visibility for eleven headlamp configurations.”
10. Sukwon Kim (2003) “Relationships between hamstring activation rate and biomechanics of slip-induced falls among young and older adults.”
11. Laura Hughes (2004) “Effects of time pressure and mental workload on physiological risk factors for upper extremity musculoskeletal disorders while typing.”
12. Grace Tran (2004) “Assistive intervention in the characterization of muscle activity during bed rising and assessment of self-perceived recovery measures for abdominal surgery patients in postoperative care.”
13. Bradley Davidson (ESM, 2005) “Biomechanical evaluation of lumbar extensor fatigue effects on the postural control system.”
14. Ellen Rogers (ESM, 2005) “Prolonged lumbar trunk flexion disturbs paraspinal reflex behavior”.
15. Sajitha Narayan (2005) “Comparison of various display representation formats for older adults using in lab and remote usability testing.”
16. Kevin Pline (ESM, 2005) “Effects of lumbar extensor fatigue on ankle joint motion sense and prolonged effect on postural sway.”

17. Tolga Durak (2005) "Design and testing of an adult age-independent online needs assessment tool and development of adult age-independent design guidelines."
18. Christine Hermann (ESM, 2005) "Estimating joint torques on a Biodex System 3 dynamometer."
19. Monica Glumm (2005) "Effects of increases in mental workload on avoidance of ground hazards."
20. Ian Bertmaring (2006) "Using thermography to evaluate the effects of arm flexion and loading on the anterior deltoid during a simulated overhead task."
21. Kathleen Bieryla (BME, 2006) "A preliminary study of trip recovery training in older adults for use as a fall prevention intervention."
22. Yogesh Bhatkhande (2006) "Comparison of traditional and activity theory based analysis methods for verbal protocol data."
23. Ira Jhangiani (2006) "A cross-cultural comparison of cell phone interface design preferences from the perspective of nationality and usability."
24. Yoon Lee (2007) "An approach to identify effective learning outcomes for a training program."
25. Michael Whitley (BME, 2008) "Maximum absolute and relative joint torques during recovery from a simulated trip."
26. Sara Matrangola (BME, 2008) "A modeling investigation of obesity and balance recovery."
27. Christopher Bamberg (CEE, 2009) "Lateral movement of unbraced wood composite I-joists exposed to dynamic walking loads."
28. Paul Timko (CEE, 2009) "Finite element analysis of unbraced structural wood I-joists under construction loads."
29. Kerry E. Costello (BME, 2011) "Understanding the independent effects of inertia and weight on balance."
30. Anuj Mistry (2011) "Effects of Yoga on low back stability, strength, and endurance."
31. Navaneeta Dorbala (2012) "Quantification of cumulative load on the knee using a vibration emission method."
32. Danielle Beringer (BME, 2013) "An exploratory study investigating the time duration of slip-induced changes in gait."
33. Matthias Treff (2014) "An investigation of musculoskeletal imbalances in the thoracic and cervical regions, with respect to an improved diagnostic approach for Upper Crossed Syndrome."
34. John Scanlon (BME, 2014) "Comparing gait between outdoors and inside a laboratory."
35. Leigh Allin (ESM, 2014) "A study on the effects of obesity and age on balance recovery after slipping."

Other Academic Advising Responsibilities:

Post-doctoral Researchers

1. Dr. Laura L. Clark (01/98 – 12/98)
2. Dr. Hardianto Iridiastadi (01/04 – 08/04)
3. Dr. Hyang Seol (12/04 – 06/07)
4. Dr. Yassierli (11/05 – 07/06)
5. Dr. Seokhee Na (09/07 – 02/09)
6. Dr. Babak Bazrgari (02/09 – 07/11)
7. Dr. Sunwook Kim (01/13 – present)

Visiting Researchers and Research Scholars

1. Mr. Kei Tomioka; Toshiba Corp., Japan (01/00 – 10/1/00)
2. Mr. Yassierli; Institut Teknologi Bandung, Indonesia (03/01 – 08/01)

3. Ms. Renate van Zandwick; MS student, Free University, Amsterdam, The Netherlands (03/04 – 08/04)
4. Ms. Yang Pan; Doctoral Student, Shanghai Maritime University, China (02/09 – 05/09)
5. Mr. Matthew Ruder; Undergraduate student, St. Louis University, Bioengineering/Bioinformatics Summer Institute (06/10 – 08/10)
6. Dr. Cai Gui; Space Ergonomics Laboratory, Astronaut Center of China (08/10 – 08/11)
7. Dr. Li Li, School of Arts and Media, Wuhan Polytechnic University (02/13 – 01/14)
8. Ms. Bhatt, PhD Fulbright Scholar, India (12/13 – 06/14)

Undergraduate Independent Research (ISE 4994)
1. Mr. Dean Owen (Fall 1997)
2. Ms. Laura Stanley (Spring 1998)
3. Mr. Adam Grossman (Spring 1999)
4. Mr. Scott Maulsby (Spring 1999)
5. Ms. Julie Gist (Spring 1999)
6. Mr. Mike McNulty (Fall 2000)
7. Mr. Erik Power (Spring 2000)
8. Mr. Kris Hager (Spring 2001)
9. Mr. Don Haga (Fall 2001)
10. Mr. Dan Bernard (Spring 2004)
11. Mr. Matthew Sondrup (Fall 2004)
12. Mr. Nathan Fleming (Fall 2004)
13. Ms. Alice Haskins (Fall 2006)
14. Ms. Erin Mahony (Spring 2008)
15. Mr. Josh Dowden (Spring 2008)
16. Mr. Rory Brannan (Fall 2008)
17. Mr. Leif Alleman (Spring 2009)
18. Mr. Josh Halferty (Spring, 2009)

Student Awards:

Angela DiDomenico Astin
- American Society of Safety Engineers; Duermier Safety Scholarship ($1000, March, 1998)
- American Society of Safety Engineers; Thompson Scholarship for Women in Safety ($1000, May, 2000)
- Jean B. Duerr Memorial Scholarship ($1500, April, 2001)

Miguel Perez
- General Motors Corp. Hispanic Scholarship ($2500, March, 1999)
- National Research Council: Ford Foundation Pre-Doctoral Fellowship ($17,000/yr for 3 years; 9/99-8/02)
- Best Student Paper, Industrial Ergonomics Technical Group, Human Factors and Ergonomics Society ($500, December, 2002)

Hardianto Iridiastadi
- Indonesian Cultural Foundation Scholarship ($4000, 2002)

Yassierli
- Best Student Paper, Industrial Ergonomics Technical Group, Human Factors and Ergonomics Society ($500, September, 2004)

Xingda Qu
- VT College of Engineering Fellowship (08/04 – 08/08)

Linsey Barker

- VT College of Engineering Teaching Fellowship (08/06 – 05/09)
- Alpha Pi Mu National Award of Excellence ($500, June, 2008)
- Humantech Doctoral Scholarship ($1500, December, 2008)
- VT Graduate Teaching Assistant Excellence Award ($1000, February, 2009)

Bochen Jia

- Jean B. Duerr Memorial Scholarship ($2000, February, 2008)

Sunwook Kim

- ISE Grado Graduate Fellowship, VT ISE (stipend + tuition; 08/08-08/10)

Lora Cavuoto

- VT College of Engineering Teaching Fellowship (08/09 – 08/11)
- ISE UPS Fellowship (08/11 – 05/12)

Ehsan Rashedi

- Best Research Presentation (poster), VT Graduate Student Research Symposium ($550, March 27, 2013)
- 2nd place, graduate student research presentation, ASSE Professional Development Conference (2013)
- Research Travel Grant, ASSE (2013)
- Diversity Scholar, Office of Recruitment and Diversity Initiative, VT ($300, 2014)

Other:

Adolescent Counselor (1990-1995)

University of Michigan Medical School – Completed all academic (non-clinical) requirements and passed National Board Exam Part I (1984)

Board Certified Professional Ergonomist (BCPE, 1995)

PEER REVIEWED PUBLICATIONS:

Underlined authors are mentored students or research staff.

1. Moga, P.J., Erig, M., Chaffin, D.B. and **Nussbaum, M.A.** (1993) Torso muscle moment arms at intervertebral levels T10 through L5 from CT scans on 11 male and 8 female subjects. *Spine*, **18**, 2305-2309.
2. **Nussbaum, M.A.**, Chaffin, D.B. and Martin, B.J. (1995) A backpropagation neural network model of lumbar muscle recruitment during moderate static exertions. *Journal of Biomechanics,* **28**, 1015-1024.
3. **Nussbaum, M.A.**, Chaffin, D.B. and Rechtien, C.J. (1995) Muscle lines-of-action affect predicted forces in optimization-based spine muscle modeling. *Journal of Biomechanics,* **28**, 401-409.
4. **Nussbaum, M.A.** and Chaffin, D.B. (1996) Development and evaluation of a scalable and deformable geometric model of the human torso. *Clinical Biomechanics,* **11**, 25-34.
5. **Nussbaum, M.A.** and Chaffin, D.B. (1996) Evaluation of artificial neural network modeling to predict torso muscle activity. *Ergonomics*, **39**, 1430-1444.
6. **Nussbaum, M.A.** and Chaffin, D.B. (1997) Pattern classification reveals intersubject group differences in lumbar muscle recruitment during static loading. *Clinical Biomechanics*, **12**, 97-106.
7. **Nussbaum, M.A.**, Martin, B.J. and Chaffin, D.B. (1997) A neural network model for simulation of torso muscle coordination. *Journal of Biomechanics*, **30**, 251-258.
8. **Nussbaum, M.A.** and Chaffin, D.B. (1998) Lumbar muscle force estimation using a subject-invariant 5-parameter EMG-based model. *Journal of Biomechanics*, **31**, 667-672.
9. Chaffin, D.B., Stump, B.S., **Nussbaum, M.A.** and Baker G. (1999) Low back stresses when learning to use a materials handling device. *Ergonomics,* **42**, 94-110.
10. **Nussbaum, M.A.** and Chaffin, D.B. (1999) Effects of pacing when using material handling manipulators. *Human Factors,* **41**, 214-225.
11. **Nussbaum, M.A.**, Chaffin, D.B. and Baker, G. (1999) Biomechanical analysis of material handling manipulators in short distance transfers of moderate mass objects: joint strength, spine forces, and muscular antagonism. *Ergonomics*, **42**, 1597-1618.
12. **Nussbaum, M.A.**, Chaffin, D.B., Stump, B.S., Baker, G. and Foulke, J. (2000) Motion times, hand forces, and trunk kinematics when using material handling manipulators in short distance transfers of moderate mass objects. *Applied Ergonomics*, **31**, 227-237.
13. Zhang, X., **Nussbaum, M.A.** and Chaffin, D.B. (2000) Back lift versus leg lift: an index and visualization of dynamic lifting strategies. *Journal of Biomechanics*, **33**, 777-782.
14. **Nussbaum, M.A.** and Zhang, X. (2000) Heuristics for locating upper extremity joint centers from surface markers: empirical derivation, evaluation, and optimization-based enhancement. *Human Movement Science*, **19**, 797-816.
15. **Nussbaum, M.A.** and Torres, N. (2001) Effects of training in modifying working methods during common patient handling tasks. *International Journal of Industrial Ergonomics*, **27**, 33-41.
16. **Nussbaum, M.A.** (2001) Static and dynamic myoelectric measures of shoulder muscle fatigue during intermittent dynamic exertions of low to moderate intensity. *European Journal of Applied Physiology*, **85**, 299-309.
17. **Nussbaum, M.A.**, Clark, L., Kirst, M. and Rice, K. (2001) Fatigue and endurance limits during intermittent overhead work. *American Industrial Hygiene Association Journal,* **62**, 446-456.
18. **Nussbaum, M.A.** and Johnson, H. (2002) Determination and evaluation of acceptable force limits in single digit tasks. *Human Factors*. **44**, 545-556.

19. Perez, M.A. and **Nussbaum, M.A.** (2002) Lower torso muscle activation patterns for high-magnitude static exertions: gender differences and the effects of twisting. *Spine*. **27**, 1326-1335.
20. DiDomenico, A. and **Nussbaum, M.A.** (2003) Measurement and prediction of single and multi-digit finger strength. *Ergonomics*. **46**, 1531-1548.
21. Johnson, H. and **Nussbaum, M.A.** (2003) Strength and subjective limits for repetitive manual insertion tasks. *American Industrial Hygiene Association Journal*. **64**, 763-770.
22. **Nussbaum, M.A.** (2003) Postural stability is compromised by fatiguing overhead work. *American Industrial Hygiene Association Journal*. **64**, 56-61.
23. Perez, M.A. and **Nussbaum, M.A.** (2003) Principal components analysis as an evaluation and classification tool for lower torso sEMG data. *Journal of Biomechanics*. **36**, 1225-1229.
24. Saleem, J.J., Kleiner, B.M. and **Nussbaum, M.A.** (2003) Empirical evaluation of training and a work analysis tool for participatory ergonomics. *International Journal of Industrial Ergonomics*. **31**, 387-396.
25. Smith-Jackson, T.L., **Nussbaum, M.A.** and Mooney, A.M. (2003) Accessible cell phone design: development and application of a needs analysis framework. *Disability and Rehabilitation*. **25**, 549-560.
26. Davidson, B.S., Madigan, M.L. and **Nussbaum, M.A.** (2004) Effects of lumbar extensor fatigue and fatigue rate on postural sway. *European Journal of Applied Physiology*. **93**, 183-189.
27. Edwards, G.W., Barfield, W. and **Nussbaum, M.A.** (2004) Use of force feedback and auditory cues for performance of an assembly task in an immersive virtual environment. *Virtual Reality*. **7**, 112-119.
28. DiDomenico, A. and **Nussbaum, M.A.** (2005) Interactive effects of mental and postural demands on subjective assessment of mental workload and postural stability. *Safety Science*. **43**, 485-495.
29. **Nussbaum, M.A.** and Lang, A. (2005) Relationships between static load acceptability, ratings of perceived exertion, and biomechanical demands. *International Journal of Industrial Ergonomics*. **35**, 547-557.
30. Pline, K.M., Madigan, M.L., **Nussbaum, M.A.**, and Grange, R.W. (2005) Lumbar extensor fatigue and circumferential ankle pressure impair ankle joint motion sense. *Neuroscience Letters.* **390**, 9-14.
31. Iridiastadi, H. and **Nussbaum, M.A.** (2006) An evaluation of cumulative probability distribution of force (CPDF) as an exposure assessment method during isometric non-isotonic shoulder abductions. *International Journal of Industrial Ergonomics*. **36**, 37-43.
32. Iridiastadi, H. and **Nussbaum, M.A.** (2006) Muscle fatigue and endurance during repetitive intermittent static efforts: development of prediction models. *Ergonomics*. **49**, 344-360.
33. Iridiastadi, H. and **Nussbaum, M.A.** (2006) Muscular endurance and fatigue during intermittent static efforts: effects of contraction level, duty cycle, and cycle time. *Human Factors*. **48**, 710-720.
34. Lee, Y.S., Hong, S.W., Smith-Jackson, T.L., **Nussbaum, M.A.** and Tomioka, K. (2006) Systematic evaluation methodology for cell phone user interfaces. *Interacting with Computers*. **18**, 304-325.
35. Madigan, M.L., Davidson, B. and **Nussbaum, M.A.** (2006) Postural sway and joint kinematics during quiet standing are affected by lumbar extensor fatigue. *Human Movement Science*. **25**, 788-799.
36. Perez, M. and **Nussbaum, M.A.** (2006) Posture and motion variability in non-repetitive manual materials handling tasks. *Human Movement Science*. **25,** 409-421.
37. Pline, K.M., Madigan, M.L. and **Nussbaum, M.A.** (2006) Influence of fatigue time and fatigue level on increases in postural sway. *Ergonomics*. **49**, 1639-1648.

38. Wilson, E.L., Madigan, M.L., Davidson, B.S. and **Nussbaum, M.A.** (2006) Postural strategy changes with fatigue of the lumbar extensor muscles. *Gait & Posture*. **23**, 348-354.
39. Anderson, D.E., Madigan, M.L. and **Nussbaum, M.A.** (2007) Maximum voluntary joint torque as a function of joint angle and angular velocity: model development and application to the lower limb. *Journal of Biomechanics*. **40**, 3105-3113.
40. Bieryla, K., Madigan, M.L. and **Nussbaum, M.A.** (2007) Practicing recovery from a simulated trip improves recovery kinematics after an actual trip. *Gait & Posture.* **26**, 208-213.
41. Krausman, A. and **Nussbaum, M.A.** (2007) Effects of wearing chemical protective clothing on text entry when using wearable input devices. *International Journal of Industrial Ergonomics.* **37**, 525-530.
42. Kyung, G., **Nussbaum, M.A.**, Lee, S., Kim, S. and Baek, K. (2007) Sensitivity of preferred driving postures and determination of core seat track adjustment ranges. *SAE Technical Paper Series*, 2007-01-2471.
43. Ryu, Y.S., Babski-Reeves, K.L., Smith-Jackson, T. and **Nussbaum, M.A.** (2007) Decision models for comparative usability evaluation of mobile phones using the Mobile Phone Usability Questionnaire (MPUQ). *Journal of Usability Studies*, **3**, 24-40.
44. Sood, D., **Nussbaum, M.A.** and Hager, K. (2007) Fatigue during prolonged intermittent overhead work: reliability of measures and effects of working height. *Ergonomics*. **50**, 497-513.
45. Qu, X., **Nussbaum, M.A.** and Madigan, M.L. (2007) A balance control model based on an optimal control strategy. *Journal of Biomechanics.* **40**, 3590-3597.
46. Yassierli and **Nussbaum, M.A.** (2007) Muscle fatigue during intermittent isokinetic shoulder abduction: age effects and utility of electromyographic measures. *Ergonomics*. **50**, 1110-1126.
47. Yassierli, **Nussbaum, M.A.**, Iridiastadi, H. and Wojcik, L. (2007) The influence of age on isometric endurance and fatigue is muscle dependent: a study of shoulder abduction and torso extension. *Ergonomics*. **50**, 26-45.
48. Bertmaring, I., Babski-Reeves, K. and **Nussbaum, M.A.** (2008) Infrared imaging of the anterior deltoid during overhead static exertions. *Ergonomics*. **51**, 1606-1619.
49. DiDomenico, A. and **Nussbaum, M.A.** (2008) Estimation of forces exerted by the fingers using standardized surface EMG from the forearm. *Ergonomics*. **51**, 858-871.
50. DiDomenico, A. and **Nussbaum, M.A.** (2008) Interactive effects of physical and mental workload on subjective workload assessment. *International Journal of Industrial Ergonomics*. **38**, 977-983.
51. Iridiastadi, H., **Nussbaum, M.A.** and van Dieën, J.H. (2008) Muscular load characterization during isometric non-isotonic shoulder abductions with varying force. *Journal of Electromyography and Kinesiology.* **18**, 695-703.
52. Kim, S., **Nussbaum, M.A.** and Madigan, M.L. (2008) Direct parameterization of postural stability during quiet upright stance: effects of age and altered sensory conditions. *Journal of Biomechanics*. **41**, 406-411.
53. Kim, S., Seol, H., Ikuma, L.H. and **Nussbaum, M.A.** (2008) Knowledge and opinions of designers of industrialized wall panels regarding incorporating ergonomics in design. *International Journal of Industrial Ergonomics*. **38**, 150-157.
54. Kyung, G., **Nussbaum, M.A.** and Babski-Reeves, K. (2008) Driver sitting comfort and discomfort (part I): use of subjective ratings in discriminating car seats and correspondence among ratings. *International Journal of Industrial Ergonomics*. **38**, 516-525.
55. Kyung, G. and **Nussbaum, M.A.** (2008) Driver sitting comfort and discomfort (part II): relationships with and prediction from interface pressure. *International Journal of Industrial Ergonomics*. **38**, 526-538.

56. Lee, J.H., Kwon, B.K., Kyung, G. and **Nussbaum, M.A.** (2008) Predicting driving postures and seated positions in SUVs using a 3D digital human modeling tool. *SAE Technical Paper Series*. 2008-01-1856.
57. Lin, D., Seol, H., **Nussbaum, M.A.** and Madigan, M.L. (2008) Reliability of COP-based postural sway measures and age-related differences. *Gait & Posture*. **28**, 337-342.
58. Matrangola, S.L., Madigan, M.L., **Nussbaum, M.A.**, Ross, R. and Davy, K.P. (2008) Changes in body segment inertial parameters of obese individuals with weight loss. *Journal of Biomechanics*. **41**, 3278-3281.
59. Perez, M.A. and **Nussbaum, M.A.** (2008) A neural network-based posture prediction model for non-repetitive manual materials handling tasks. *Ergonomics*. **51**, 1549-1564.
60. Tran, G., Babski-Reeves, K.L. and **Nussbaum, M.A.** (2008) Electromyographic evaluation of a bed assistive device for abdominal surgery patients in postoperative care. *Human Factors*. **50**, 237-255.
61. Yassierli and **Nussbaum, M.A.** (2008) Utility of traditional and alternative EMG-based measures of fatigue during low-level isometric efforts. *Journal of Electromyography and Kinesiology.* **18**, 44-53.
62. Anderson, D.E., Madigan, M.L. and **Nussbaum, M.A.** (2009) An algorithm for directly fitting a torque-angle-angular velocity model to maximum voluntary joint torques measured with an isokinetic dynamometer. *Isokinetics and Exercise Science*. **17**, 51-56.
63. Davidson, B.S., Madigan, M.L., **Nussbaum, M.A.** and Wojcik, L.A. (2009) Effects of localized muscle fatigue on recovery from a postural perturbation without stepping. *Gait & Posture*. **29**, 552-557.
64. Ikuma, L.H., Babski-Reeves, K. and **Nussbaum, M.A.** (2009) Experimental manipulation of psychosocial exposure and questionnaire sensitivity in a simulated manufacturing setting. *International Archives of Occupational and Environmental Health*. **82**, 735-746.
65. Ikuma, L.H., **Nussbaum, M.A.** and Babski-Reeves, K.L. (2009) Reliability of physiological and subjective responses to physical and psychosocial exposures during a simulated manufacturing task. *International Journal of Industrial Ergonomics*. **39**, 813-820.
66. Kim, S., Barker, L.M., Jia, B., Agnew, M.J. and **Nussbaum, M.A.** (2009) Effects of two hospital bed design features on physical demands and usability during brake engagement and patient transportation: a repeated measures experimental study. *International Journal of Nursing Studies*. **46**, 317-325.
67. Kyung, G. and **Nussbaum, M.A.** (2009) Specifying comfortable driving postures for ergonomic design and evaluation of the driver workspace using digital human models. *Ergonomics*. **52**, 939-953.
68. Lin, D., **Nussbaum, M.A.**, Seol, H., Singh, N.B., Madigan, M.L. and Wojcik, L.A. (2009) Acute effects of localized muscle fatigue on postural control and patterns of recovery during upright stance: influence of fatigue location and age. *European Journal of Applied Physiology*. **106**, 425-434.
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141. *Rossi, C.*, Matrangola, S., **Nussbaum, M.A.** and Madigan, M. (2013) Effects of age and obesity of risk of tripping during level walking. *Proceedings of the American Society of Biomechanics Conference*, Omaha, NE. September 4-7. Online only (2 pp.).
142. *Pau, M.*, Leban, B., Paderi, M. and **Nussbaum, M.A.** (2013) Characterization of pulling forces exerted by primary school children while carrying trolley bags. *Proceedings of the Human Factors and Ergonomics Society 57th Annual Meeting*, San Diego, CA. September 30 – October 4. pp. 501-505.
143. *Kim, S.* and **Nussbaum, M.A.** (2014) Predicting ergonomic exposures: case study on panelized wall handling. Presented at the *Industrial and Systems Engineering Research Conference.* Montréal, Canada. May 31-June 3. Abstract only.
144. *Kim, S.* and **Nussbaum, M.A.** (2014) Inertial motion capture system accuracy in estimating balance-related metrics. Presented at the *Industrial and Systems Engineering Research Conference.* Montréal, Canada. May 31-June 3. Abstract only.
145. *Allin, L.J.*, Wu, X., **Nussbaum, M.A.** and Madigan, M.L. (2014) Obesity increases fall risk after slipping among young adults. *Proceedings of the 7th World Congress of Biomechanics*, Boston, MA. Online only (1 p.).
146. *Arena, S.L.*, Garman, C.R., **Nussbaum, M.A.**, Franck, C.T. and Madigan, M.L. (2014) Required coefficient of friction decreases with increasing gait speed among older obese females. *Proceedings of the 7th World Congress of Biomechanics*, Boston, MA, July 6-11.
147. *Garman, C.R.*, Scanlon, J.M., **Nussbaum, M.A.** and Madigan, M.L. (2014) Effects of age and obesity on the likelihood of tripping during anterior load carriage. *Proceedings of the 7th World Congress of Biomechanics*, Boston, MA, July 6-11.
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149. *Scanlon, J.M.*, **Nussbaum, M.A.** and Madigan, M.L. (2014) Gait differences between inside a laboratory and outdoors. *Proceedings of the 7th World Congress of Biomechanics*, Boston, MA, July 6-11.
150. *Wu, X.*, Madigan, M.L. and **Nussbaum, M.A.** (2014) Plantar sensitivity is impaired among young adults with high BMI. *Proceedings of the 7th World Congress of Biomechanics*, Boston, MA, July 6-11.

151. *Hu, B.*, Ning, X. and Nussbaum, M.A. (2014) The influence of hand load on lumbar-pelvic coordination during lifting task. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Chicago, IL. October 27-31. pp. 1617-1621.
152. *Madigan M.L.*, Koushyar, H., Nussbaum, M.A., Davy, K.P. (2015) Effects of obesity on lower extremity strength are joint specific. *Annual Meeting of the American College of Sports Medicine*, San Diego, CA, May 26-30. Abstract only.
153. *Fino, P.C.*, Brolinson, P.G., Lockhart, T.E., Nussbaum, M.A. (2015). Non-straight gait shows greater dual-task cost than straight gait in recently concussed athletes compared to matched controls: A preliminary investigatio*n. American Society of Biomechanics Midwest Regional Meeting*, Akron, OH, February 17-18. Abstract only.

BOOK CHAPTERS:

1. **Nussbaum, M.A.** (1998) Center of mass. *Industrial and Occupational Ergonomics: Users Encyclopedia*, Mital, A. (ed.), The International Journal of Industrial Engineering. (CD, not paginated)
2. DiDomenico, A., and **Nussbaum, M.A.** (1998) Intraabdominal Pressure. *Industrial and Occupational Ergonomics: Users Encyclopedia*, Mital, A. (ed.), The International Journal of Industrial Engineering. (CD, not paginated)
3. Dieën, J.H. van and **Nussbaum, M.A.** (2004) Trunk. In *Working Postures and Movements: Tools for Evaluation and Engineering*, Delleman, N.J., Haslegrave, C.M. and Chaffin, D.B. (eds.), CRC Press LLC, Boca Raton, FL, pp. 109-141.
4. **Nussbaum, M.A.** and Dieën, J.H. van (2006) Physical Ergonomics. *The Mechanical Engineers' Handbook* (3rd Edition), Kutz, M. (ed.), Wiley & Sons, Inc., Hoboken, NJ, pp. 762-781.
5. **Nussbaum, M.A.** and Dieën, J.H. van (2015) Physical Ergonomics. *The Mechanical Engineers' Handbook* (4th Edition), Kutz, M. (ed.), Wiley & Sons, Inc., Hoboken, NJ, pp. XX-XX. (In Press)

TECHNICAL REPORTS:

1. Nussbaum, M.A., Clark, L., Kirst, M. and Rice, K. (1999) *Quantifying time-to-fatigue during short cycle overhead work operations*. Final report prepared for The American Automobile Manufacturers Association.
2. Astin, A.D. and Nussbaum, M.A. (2000) *Review of existing workload assessment tools, with special emphasis on subjective methodologies*. Final report prepared for Individual Performance Branch, ARL-HRED.
3. Nussbaum, M.A. and Johnson, H. (2001) *Hand force limits for manual insertion tasks*. Final report prepared for Honda of America Manufacturing, Inc.
4. Nussbaum, M.A. (2001) *Evaluation of the USPS DEAT Process*. Final report prepared for the United States Postal Service.
5. Smith-Jackson, T.L., Mooney, A. and Nussbaum, M.A. (2001) *Survey on technology needs for disabled persons*. Final report prepared for Toshiba Corporation.
6. Mooney, A., Nussbaum, M.A. and Smith-Jackson, T.L. (2002) *Accessibility of notebook computers: issues and recommendations*. Final report prepared for Toshiba Corporation.
7. Mooney, A., Nussbaum, M.A. and Smith-Jackson, T.L. (2002) *Accessibility of cellular phones: design recommendations*. Final report prepared for Toshiba Corporation.
8. Nussbaum, M.A., Sood, D. and Hager, K. (2002) *Recommended limits for overhead work.* Final report prepared for Honda of America Manufacturing, Inc.
9. Smith-Jackson, T.L., Nussbaum, M.A., Lee, Y.S. and Hong, S.W. (2003) *Usability inspection, testing, and evaluation of cell phone user interfaces*. Final report prepared for Toshiba Corporation.

10. Nussbaum, M.A., Babski-Reeves, K.L., Sood, D. and Kant, R. (2004) *Recommended limits for manual torquing tasks.* Final report prepared for Honda of America Manufacturing, Inc.
11. Smith-Jackson, T.L., Nussbaum, M.A., Lee, Y.S., Ryu, Y.S. and Shin, D.J. (2004) *Design, testing, and verification of the cellular phone navigation system*. Final report prepared for Toshiba Corporation.
12. Nussbaum, M.A., Yassierli, and Iridiastadi, H. (2004) *Age effects on intermittent work capacity*. Final report prepared for NIOSH.
13. Nussbaum, M.A. and Madigan, M.L. (2008) *Risk factors and controls for falls from heights*. Final report prepared for NIOSH.
14. Nussbaum, M.A., Shewchuk, J.P. and Kim, S. (2009) *A decision support system for ergonomic construction design*. Final report prepared for NIOSH.
15. Nussbaum, M.A., Agnew, M.J., Rashedi, E. and Kim, S. (2012) *Ergonomic research on manufacturing tasks*. Final report prepared for Equipois, Inc.

INVITED TALKS, PAPERS, and SEMINARS:

1. *Ergonomic Assessment of Office Operations.* Nussbaum, M.A. and Monroe, K.A. Presented at The 28th Annual Big Ten Printing Conference, Ann Arbor, MI, 1994.
2. Nussbaum, M.A. (1996) *Book Reviews*, Journal of Biomechanics, 29, 1399-1400.
3. *Case studies in the measurement of low back muscular fatigue*. Sponsored by the American Automobile Manufacturers Association, Ergonomics Task Group, Muscle Fatigue Workshop, Detroit, MI (July 22-23, 1997).
4. *Use of electromyography to estimate lumbar muscle forces during unconstrained exertions*. Sponsored by NIOSH, Division of Safety Research, Protective Technology Branch, Morgantown, WV (July 30, 1997)
5. Nussbaum, M.A., Chaffin, D.B., and Martin, B.J. (1995) A back-propagation neural network model of lumbar muscle recruitment during moderate static exertions. *J. Biomechanics,* 28, 1015-1024. Invited paper in: van Bemmel, J.H. and McCray, A.T. (eds.), *Yearbook of Medical Informatics 1997*, Schattauer, pp. 450-459.
6. *Artificial neural networks for analysis and simulation of lumbar muscle coordination*. North Carolina State University, Department of Industrial Engineering, Raleigh, NC (February 26, 1999)
7. Nussbaum, M.A. (2000) *Book Review*, Journal of Biomechanics, 33, 1047.
8. *Current trends in ergonomics research and legislation*. Presented at the Central Virginia Section of the American Industrial Hygiene Association, Richmond, VA. (April 27, 2000).
9. *Biomechanics of the Shoulder and Neck.* Presented as part of a 1-day Ergonomics Seminar at the State-of-the-Art Conference (SOTAC), Nashville, TN. Sponsored by the American College of Occupational and Environmental Medicine and the Academy of Industrial Hygiene. (October 29, 2000).
10. *Practical tools for ergonomic assessment and evaluation.* Presented at the *Virginia Occupational Safety and Health Conference (VOSH)*, Portsmouth, VA. Sponsored by the Virginia Department of Labor and Industry. (June 28, 2001).
11. *Localized Muscle Fatigue: Current Issues and Research.* Invited Seminar (1 hr) presented to Army Research Laboratory, Human Research and Engineering Directorate, Aberdeen Proving Ground, MD, as part of Professional Development Seminar Series. (February 12, 2002)
12. *Development and evaluation of models for prediction of lumbar muscle activity and coordination*. Invited Seminar (1 hr) presented to the Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign. (April 2, 2002)
13. *Localized muscle fatigue: Current issues, research, and applications*. Invited Seminar (1 hr) presented to the Department of Industrial Engineering, University at Buffalo, Buffalo, NY. (March 12, 2004)

14. *Measuring and predicting localized muscle fatigue during complex tasks performed at low-moderate levels of exertion.* Invited Seminar (1 hr) presented to the Center for Ergonomics, Industrial and Operations Engineering, The University of Michigan, Ann Arbor, MI. (November 9, 2004)
15. *Needs for and potential applications of basic biomechanics research in occupational biomechanics*. Invited Symposium speaker ("Future Directions in Occupational Biomechanics"). *Proceedings of the American Society of Biomechanics Annual Conference*. Blacksburg, VA. September 6-9, 2006. (CD only, not paginated)
16. *Developing a decision support tool for ergonomic construction design*. Invited speaker (1/2 hour) at the *Occupational Biomechanics Symposium: Celebrating 35 Years of Progress and Looking Toward the Future*, Ann Arbor, MI. (November 16-17, 2006)
17. *Repetitive work cycles and localized muscle fatigue.* Invited speaker (3/4 hour) at the UC Berkeley Center for Occupational and Environmental Health's Continuing Education Program - *Ergonomic Interventions and Research: Preventing Workplace Musculoskeletal Disorders*, San Francisco, CA. (December 14-15, 2006).
18. *A decision support tool for ergonomic construction design: conceptual approach and preliminary results*. Invited Seminar (1 hr) presented to the Department of Industrial Engineering, University at Buffalo, Buffalo, NY. (April 18, 2008)
19. *A decision support system for ergonomic construction design: development and initial results*. Invited Keynote (1 hr) presented as the 6th Annual Paul S. Richards, MD, Endowed Distinguished Visiting Lectureship in Occupational Medicine, at the 7th Annual Regional NORA Young/New Investigators Symposium, University of Utah, Salt Lake City, UT (April 16-17, 2009)
20. *Improving productivity and worker health in panelized construction: achieving PtD using simulation*. Invited talk (20 min) presented at the 2009 NORA Construction Research Workshop and Sector Council Meeting. Washington, DC. (November 3-4, 2009)
21. *Strategies for effective grant writing*. Invited graduate student seminar (1 hr) sponsored by AdvanceVT (NSF). Blacksburg, VA. (February 4, 2010)
22. *Ergonomic evaluations of hospital bed design features*. Invited seminar (1 hr) given to the Center for Worker Health, Wake Forest University School of Medicine, Winston-Salem, NC. (September 29, 2010)
23. *Strategies for effective grant writing*. Invited graduate student seminar (1 hr) invited by the VT Department of Psychology. Blacksburg, VA. (February 25, 2011)
24. *Occupational ergonomics and biomechanics: overview of past and present research*. Invited talk (1 hr) at the *17th Meeting of the NIOSH Cross-Sector Program for MSDs*. Columbus, OH. (April 7, 2011)
25. *Occupational trunk flexion and neuromuscular disturbance*. Invited seminar (1 hr.), Department of Industrial and Operations Engineering, The University of Michigan, Ann Arbor, MI (September 19, 2012)
26. *Development of a comprehensive intervention approach for residential construction using prefabricated walls (panels)*. Invited talk (1/2 hour), Southeastern Occupational Network (SouthON) Meeting, Tampa, FL (December 4, 2012)
27. *Occupational muscle fatigue*: measurement, modeling, and consequences. Invited talk (1 hour), School of Design & Human Engineering, UNIST, Ulsan, South Korea (April 1, 2013)
28. *Development of a comprehensive ergonomics intervention approach for residential construction using prefabricated walls (panels)*. Invited talk (1 hour), School of Biological Science and Medical Engineering, Beihang University, Beijing China (April 10, 2013)
29. *Development of a comprehensive ergonomics intervention approach for residential construction using prefabricated walls (panels)*. Invited talk (1 hour), Department of Industrial Engineering, Tsinghua University, Beijing China (April 11, 2013)

30. Xia, T., Nussbaum, M.A. and Ma, L. (2015) Preface to Special Issue on "Muscle Strength and Fatigue Modelling – Theory, Development and Implementation. *International Journal of Human Factors Modeling and Simulation*. **5**, 1-4.

PROFESSIONAL SERVICE:

Archival Journals:

- Founding and Managing Editor, *IIE Transactions on Occupational Ergonomics and Human Factors* (06/10 – present)

- Editorial Board Member, *American Industrial Hygiene Association Journal* (03/02 – 12/03) -> *Journal of Occupational and Environmental Hygiene* (01/04 – present)
- Editorial Board Member, *Journal of Applied Biomechanics* (11/02 – 10/09)
- Editorial Board Member, *Ergonomics* (03/06 – present)
- Consulting Editor, *Journal of Biomechanics* (07/09 – present)
- Editorial Board Member, *Applied Ergonomics* (10/09 – present)

- Special Issue Editor (with Smith-Jackson and Kleiner), *Health & Safety in Construction (2011)*, 4 papers in *The Open Occupational Health & Safety Journal*
- Special Issue co-Editor (with T. Xia and L. Ma), *International Journal of Human Factors Modelling and Simulation*, "Muscle Strength and Fatigue Modelling – Theory, Development, and Implementation" (04/13 – 12/14)

- Reviewer:
  - *Regular reviewer:* Applied Ergonomics, Ergonomics, Gait & Posture, HFES Conference Papers, Institute for Ergonomics and Human Factors Conference Papers, Journal of Biomechanics, Journal of Occupational and Environmental Hygiene
  - *Occasional reviewer:* Clinical Biomechanics, European Journal of Applied Physiology, Human Factors, Human Movement Science, International Journal of Industrial Ergonomics, Journal of Applied Biomechanics, Journal of Electromyography and Kinesiology, Spine
  - *Other:* Annals of Biomedical Engineering, Automation in Construction, Computers and Industrial Engineering, European Journal of Sport Sciences, Experimental Brain Research, Human Factors and Ergonomics in Manufacturing, IEEE Trans. SMC-A, IEEE Trans. BME, IEEE Trans. NSRE, International Journal of Human Factors Modeling and Simulation, International Journal of Sports Medicine, Journal of Applied Physiology, Journal of Back and Musculoskeletal Rehabilitation, Journal of Biomechanical Engineering, Journal of Neuroscience Methods, Journal of Rehabilitation Research and Development, Medicine & Science in Sports & Exercise, Neuroscience, Neuroscience and Biobehavioral Reviews, Theoretical Issues in Ergonomics Science, Tohoku Journal of Experimental Medicine

Proposal/Grant Reviews:

- Study Section member, CDC/NIOSH Safety and Occupational Health (07/01/04 – 06/30/08).
- Review Panel member (*ad hoc*), CDC/NIOSH:
  - Safety and Occupational Health: New Orleans, LA (February 28 – March 1, 2002)
  - Safety and Occupational Health: Washington, DC (June 27 – June 28, 2002)
  - Special Study Section, Safety and Occupational Health (March 18, 2008)
  - Safety and Occupational Health: Washington, DC (February 17-18, 2009)

  - Safety and Occupational Health: Washington, DC (October 13-14, 2009)
  - Safety and Occupational Health: San Francisco, CA (June 22-23, 2010)
  - Special Emphasis Panel: Disease, Disability, and Injury Prevention and Control (July 28, 2010)
  - Chair, Special Emphasis Panel: Disease, Disability, and Injury Prevention and Control (March 9, 2011)
  - Safety and Occupational Health: Washington, DC (October 18-19, 2011)
  - Special Emphasis Panel: Disease, Disability, and Injury Prevention and Control (November 9, 2011)
  - Member Conflict Review Panel (March 7, 2012)
  - Chair, Member Conflict Review Panel (October 30, 2012)
  - Member, NIOSH NORA Review Panel (02/21/13 – 02/22/13)
  - Safety and Occupational Health: Washington, DC (February 19, 2014)
- Review Panel member (*ad hoc*), other:
  - International Collaborations in Environmental Health, NIEHS: Chapel Hill, NC (June 25-25, 2012)
  - NIOSH Occupational Safety and Health Education and Research Centers (ERCs) review panel (February 24-27, 2014)
- Reviewer and Site Visit Member (NIOSH ERC)
  - Ergonomics Program, UC Berkeley (December 2-4, 2001)
  - Occupational Safety and Ergonomics Program, UNC Chapel Hill (November 6-8, 2002)
  - Occupational Health Psychology and Occupational Safety Programs, University of South Florida (January 10-11, 2008)
- Other Proposal/Grant Reviews
  - Medical Research Scotland (2006)
  - NY/NJ NIOSH ERC (2011)
  - University of Wisconsin RGI (2011)
  - GAČR (Czech Science Foundation) (October, 2012)
  - German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF) (2013)
  - Nanyang Technical University, Singapore (2013)
  - National Sciences and Engineering Research Council, Canada (2012, 2013)
  - National Science Foundation, Ad Hoc Reviewer (2004, 2011, 2013)
  - University of Kuwait (2013)

Conferences and Other Service to Professional Organizations:

- Co-organizer (with J.H. van Dieën) of Special Symposium (4 sessions, 12 papers) at the 2000 joint meeting of the Human Factors and Ergonomics Society & The International Ergonomics Association.
- Member, Host Committee, American Society of Biomechanics (2006 conference)
- Awards Committee Member, American Society of Biomechanics (1997, 2000, 2001, 2007, 2008, 2010, 2011, 2012, 2013)
- Member, Program Committee, American Society of Biomechanics (2013 conference)
- Track Chair (with P. Dempsey), *Industrial Engineering Research Conference (IERC)*, Human Factors and Ergonomics (60 abstracts, 36 papers), May 30 – June 2, 2009
- Member, ASB Junior Faculty Mentoring Roundtable (at annual conference, 1 hr), August 19, 2010.

- Program Committee Member (November 2010 – March 2011), Session Organizer ("Applied Research", 6 talks), and Moderator, at the *Applied Ergonomics Conference*, Orlando, FL, March 21-24, 2011.
- International Planning Committee Member (October 2010 – August 2011) and Session Chair ("Design for Safety & Health I"), *CIB W099 Conference*. Washington, DC, August 24-26, 2011.
- Program Committee Member (August 2011 – March 2012) and Session Coordinator (11 talks in 4 parallel tracks), *Applied Ergonomics Conference*, Nashville, TN, March 26-29, 2012.
- Reviewer, conference paper submission (regular reviewer for the *Human Factors and Ergonomics Society* and the *Institute for Ergonomics and Human Factors).*
- Member, International Advisory Committee, *International Society for Occupational Ergonomics and Safety* (February, 2013 – present)
- Member, *IIE* Virtual Committee to Review Journals Structure (03/13 – present)

Other External Service

- Member, NIOSH Construction MSD Group (2008)
- External Reviewer, PhD Thesis, Department of Kinesiology, University of Waterloo, Canada (December, 2010)
- External Reviewer, PhD Thesis, School of Mechanical and Aerospace Engineering, Nanyang University, Singapore (October, 2013; June, 2014)

University Service:

- Member, Institutional Review Board (IRB) for Research Involving Human Subjects (7/98 – 12/04)

College Service:

- Department Representative, College of Engineering Industrial Opportunities Open House (11/97 – 12/00)
- Member, Pratt Task Force for Biomedical Engineering (7/98 - 11/98)
- Founding Member, Center for Biomedical Engineering (11/98 – 08/03)
- Core Member, VT/Wake Forest School of Biomedical Engineering and Sciences (9/03 – present)
- Guest Lecturer, ESM 1114 (9/22/98; 7/5/00)
- Member, CEUT ISE Faculty Study Group (2003 – present)
- Member, VT College of Engineering ASPIRES review panel (2003)
- Member, School of Biomedical Engineering and Sciences Faculty Search Committee (9/03 – 6/04)
- Founding member and Director, VT Center for Applied Biomechanics (01/05 – 12/10)
- Founding Member and Associate Director for Research, Center for Innovation in Construction Safety and Health (12/04 – 12/10)
- Member, School of Biomedical Engineering and Sciences Graduate Committee (08/05 – 08/08)
- Member, College of Engineering Promotion & Tenure Committee (08/08 – 08/14)
- Director, VT Occupational Safety and Health Research Center (OSHRC) (01/11 – present)

Department Service:

- Faculty Advisor, VT Student Chapter of the Human Factors and Ergonomics Society (9/96 – 08/12)
- Project Research Advisor, NIOSH Safety Training Grant (8/97 – 12/99)
- Created and oversaw a student mentoring program for incoming students in the HF/Ergonomics option (9/97 – 08/13)
- Member, ISE Seminar Committee (11/97 – 10/98)
- Coordinator, ASSE Colonial Virginia Chapter of ASSE, Deurmier Safety Scholarship (12/97 – 12/02)
- Departmental Representative, Sigma Xi (08/99 – 05/04)
- Member, ISE Honors and Awards Committee (01/00 – 08/02; 08/13 – present)
- Chair, ISE Honors and Award Committee (08/02 – 07/03)
- Director, NIOSH Occupational Safety and Health Training Grant (01/00 – present)
- Coordinator, ISE Safety Engineering Graduate Program (01/00 – present)
- Coordinator, ISE Human Factors Engineering and Ergonomics Graduate Option (01/01–08/08)
- Member, ISE Graduate Policy Committee (01/01 – present)
- Member, ISE Department Head Search Committee (05/03 – 02/04)
- Faculty mentor (Dr. Kari Babski-Reeves, 10/02 – 06/06)
- Faculty mentor (Dr. Raghu Pasupathy, 05/09 – 12/10)
- Faculty mentor (Dr. Michael Agnew, 10/07 – 01/14)
- Faculty mentor (Dr. Nathan Lau, 01/15 – present)
- Chair, ISE "Streamlined PhD" Committee (2007 – 2008)
- Chair, ISE Promotion & Tenure Committee (08/08 – 08/14)
- Member, ISE Department Head Evaluation Committee (11/08 – 04/09)
- Backup ISE IRB Reviewer (08/08 – 08/10)
- Member, ISE Collaborative Cabinet & Core Values Committee (05/10 – present)
- Member, ISE Named Professor Selection / Honorifics Committee (08/11 – present)
- Member, ISE Faculty Search Committee (08/12 – 04/13)
- Member, ISE Faculty Search Committee (08/13 – 04/14)
- Chair, ISE Graduate Policy Committee (08/14 – present)
- Chair, ISE Faculty Search Committee (09/14 – present)
- Member, ISE Graduate Admissions Committee (09/14 – present)

JAN JOURNAL OF ADVANCED NURSING

ORIGINAL RESEARCH

Fatigue, performance and the work environment: a survey of registered nurses

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Abstract

Aims. This paper is a report of a study of perceived levels of mental, physical and total fatigue, and also acute and chronic fatigue states, among registered nurses. Relationships between dimensions of fatigue and performance were investigated, as were differences in fatigue across levels of several demographic and work environment variables.

Background. Fatigue is a factor that has been linked to performance decrements in healthcare workers. As a result of the nature of their work, nurses may be particularly susceptible to multiple dimensions of fatigue, and their performance is closely linked to patient safety.

Methods. An online survey was used to measure mental, physical, and total fatigue dimensions, acute and chronic fatigue states, and performance. Participants were recruited via convenience sampling in cooperation with professional nursing organizations; 745 registered nurses completed the survey between February 2008 and April 2009.

Results. Reported mental fatigue levels were higher than physical fatigue levels, and acute fatigue levels were higher than chronic fatigue levels. All fatigue dimensions and states were negatively correlated with perceived performance. Longer shift lengths and hours worked per week were associated with increases in physical and total fatigue levels. Mental, physical and total fatigue levels also differed with shift schedule.

Conclusions. Fatigue levels were negatively correlated with performance, further supporting the role of fatigue in nurse performance. Work environment variables were strongly associated with differences in perceived levels of fatigue. By altering the work environment, it may thus be possible to reduce fatigue levels and the rates of medical errors.

Keywords: acute fatigue, chronic fatigue, nursing, performance, shift length, shift schedule, total fatigue

Introduction

High rates of medical errors and worker injuries have been established as serious contemporary challenges in the healthcare industry worldwide (Kohn *et al.* 1999, Treanor 2000, Tourangeau *et al.* 2006). As a result of their role in providing a majority of direct patient care, the performance of nurses is closely tied to the quality and safety of healthcare services (Page 2004, Tourangeau *et al.* 2006). In any given context in the healthcare domain, the specific causal or most critical factor(s) leading to safety or performance decrements may vary. Relatively few studies have considered potential pervasive factors that might influence performance across workers, tasks and environments (Howard *et al.* 2002, DeMoss *et al.* 2004, Piko 2006). Considering such context-independent factors may help to improve the quality of patient care and reduce errors more efficiently (Clarke & Aiken 2006, Tourangeau *et al.* 2006).

Background

Fatigue has been associated with stress, safety and performance decrements in numerous work environments (Ochoa *et al.* 1998, Goode 2003, Leung *et al.* 2004, 2006). Extensive evidence links fatigue with nurse injuries and adverse health consequences (Yip 2001, Geiger-Brown *et al.* 2004, Lipscomb *et al.* 2004), nurse satisfaction (Edell-Gustafsson *et al.* 2002, Josten *et al.* 2003, Taylor & Barling 2004) and patient safety (Rogers *et al.* 2004, Carayon & Gurses 2005). Fatigue is a complex construct, and which has not yet been clearly defined independent of context (Hockey 1983, Friedberg & Jason 1998, Ahsberg 2000). However, fatigue is considered generally to be a multicausal, multidimensional, non-specific and subjective phenomenon resulting from prolonged activity and psychological, socioeconomic and environmental factors that affect both the mind and the body (Soh & Crumpton 1996, Tiesinga *et al.* 1996). Although occupational fatigue is frequently defined as a multidimensional construct (Tiesinga *et al.* 1996, Ahsberg 2000, De Vries *et al.* 2003), most existing research on fatigue in nursing has focused solely on sleep, mental fatigue, emotional exhaustion and burnout components and their implications for performance and safety (Aiken *et al.* 2001, Chen & McMurray 2001, Suzuki *et al.* 2005). Nursing work is often thought of as primarily mentally versus physically demanding work, yet the physical demands associated with nursing work tasks are substantial (Trinkoff *et al.* 2001), and both mental and physical demands vary across nursing work environments. Thus, mental and physical fatigue are both likely present among nurses and a broad definition of occupational fatigue – one that includes physical and mental dimensions related to the broader construct of total fatigue – is critical for understanding the consequences of fatigue in this population.

Additionally, many existing models or definitions of occupational fatigue do not differentiate between acute and chronic fatigue states, and assume that occupational fatigue is acute (Winwood *et al.* 2005). Acute fatigue has been defined as a temporary state, commonly experienced by healthy people during the course of work or daily life activities (Aaronson *et al.* 2003). By contrast, chronic fatigue is often viewed as an illness or longer-term condition (Aaronson *et al.* 2003). In nurses, acute fatigue levels have been reported as being higher than chronic fatigue levels (Winwood *et al.* 2006b). However, given their frequent exposure to long working hours with little recovery time between shifts (Josten *et al.* 2003, Rogers *et al.* 2004, Winwood *et al.* 2006b), and the increasing prevalence of extended (e.g. 12 hours) work shifts in nursing, chronic fatigue is likely present among nurses in varying work environments and should be considered in quantifying fatigue levels in this population.

Workload, stress and other environmental factors that may influence levels of fatigue probably vary across healthcare work environments. Moreover, a majority of the existing studies investigating the relationships between work hours, workload, fatigue and performance in nursing have focused only on critical care environments (Carayon & Gurses 2005, Scott *et al.* 2006). Further research is needed to better quantify the levels of fatigue present in diverse nursing work environments.

In summary, nurses are frequently required to complete long working hours and a combination of both physically and mentally demanding tasks, which may lead to increased levels of multiple dimensions of fatigue and to acute and chronic fatigue states. Occupational fatigue has been linked to performance decrements in numerous work environments including health care; however, multiple dimensions of fatigue have not been considered in previous research. As such, the role of fatigue in medical errors and healthcare worker safety should be further clarified. Furthermore, specific work demands and stresses may vary across healthcare work environments resulting in varying levels of fatigue across contexts.

The study

Aims

The goals of this study were to quantify, among registered nurses (RNs), the perceived dimensions and states of fatigue present, to investigate the relationships between perceived fatigue and perceived performance, and to identify differences in perceived fatigue levels and dimensions across demographic and work environment variables. Given their exposure to mental and physical demands and the increasing prevalence of extended work hours, it was hypothesized that in this population: (i) mental, physical and total fatigue dimensions are all present at different levels; (ii) levels of acute fatigue exceed chronic fatigue; (iii) perceived fatigue is negatively correlated with perceived performance; and (iv) different levels of perceived fatigue exist related to demographic and work environment factors.

Design

A cross-sectional online survey was conducted with RNs in the United States of America (USA).

Participants

Registered nurses currently employed in a hospital, community or public health settings, ambulatory care, or a nursing home/extended care facility, were recruited to participate. Nurses were recruited through convenience sampling in cooperation with several nursing associations and publications. Specifically, advertisements describing the study were placed in the Virginia Nurses Association's (VNA) newsletter, Nursing Spectrum Magazine and Virginia Nurse Today publications; on the websites of the VNA and New York Nurses Association; and sent out through listservs of the VNA, Montgomery Regional Hospital (Blacksburg, VA), Arizona Nurses Association and the University of Missouri Health Systems.

Data collection

Study advertisements provided an overview of the purpose of the survey and directed participants to an online survey created using Survey Monkey (Copyright ©1999–2007 SurveyMonkey.com). To minimize recall bias, participants were instructed to complete the survey at the end of a work shift. Data collection occurred between February 2008 and April 2009.

Five survey instruments were compiled to form a 'Fatigue in Nursing Survey Set' (FNSS), which could be completed in 15–20 minutes. The instruments were selected to ensure comprehensive measurement of total, physical and mental fatigue and measures of fatigue states, performance, workload and psychosocial factors. Demographic data were also collected, including age, gender, ethnicity, years of experience, education (degree), type of healthcare organization, shift schedule and percentage of time spent on direct patient care.

Fatigue measures

Four existing scales were used to measure different aspects of fatigue. As fatigue definitions vary across contexts, fatigue measurement tools also stem from diverse conceptual models or address different dimensions of fatigue (De Vries *et al.* 2003). Multiple fatigue scales were selected to ensure comprehensive measurement of total, physical, and mental fatigue dimensions. Each has been shown previously to have acceptable levels of reliability and/or validity, and survey responses were scored according to the criteria specified for each instrument.

The Swedish Occupational Fatigue Inventory (SOFI) assessed perceived fatigue related to work across four dimensions: lack of energy, physical exertion, physical discomfort and lack of motivation (Ahsberg *et al.* 1997, Ahsberg 2000). Specifically, the SOFI lack of energy dimension was used to measure total fatigue, the lack of motivation dimension to measure mental fatigue, and the physical exertion and physical discomfort dimensions as measures of physical fatigue. This inventory contains 20 items, each rated on a seven-point scale (0 = not at all – 6 = to a very high degree). Respondents are asked to rate each item based on the extent to which they felt each expression when they were most tired. The SOFI has been tested on multiple worker populations and found to be both reliable and able to discriminate between fatigue from mental versus physical work (Ahsberg *et al.* 1997, Ahsberg 2000).

The Fatigue-Related Symptoms Questionnaire (F-RSQ) was included to measure mental and physical dimensions of fatigue (Yoshitake 1978). It consists of 16 symptoms commonly associated with fatigue, and grouped into two categories (physical and mental fatigue). The F-RSQ differs from the SOFI in that participants are asked to respond yes or no as to whether they are experiencing each symptom at the end of a work shift. The final score for each fatigue dimension is expressed as a percentage of total possible symptoms. The F-RSQ has been shown to be sensitive to fatigue levels resulting from varying work task demands (Yoshitake 1978, Murata *et al.* 1991, Soh & Crumpton 1996, Chen *et al.* 2003).

The Fatigue Scale (FAS) was used to measure total fatigue (De Vries *et al.* 2003, Michielsen *et al.* 2003, 2004), and includes 10 items rated on a 5-point rating scale (1 = never – 5 = always). This scale has good reliability and content validity for measuring fatigue in a general or worker population (De Vries *et al.* 2003, Michielsen *et al.* 2003, 2004).

To measure the fatigue states present, the Occupational Fatigue Exhaustion Recovery (OFER) scale was used

(Winwood *et al.* 2005), and which was developed to measure chronic fatigue, acute fatigue and inter-shift recovery in workers. It consists of 15 items, with responses given using a seven-point scale (ranging from 0 = strongly disagree, to 6 = strongly agree) based on experiences of fatigue and strain. Items for each subscale are summed and normalized to the maximum possible fatigue level. Final scores are then expressed as a fatigue percentage (0% = lowest possible, 100% = highest possible). This scale has been tested extensively on healthcare workers, specifically nurses, and demonstrated to have high internal and test-retest reliability and to be free of gender bias (Winwood *et al.* 2005, 2006a).

Performance measure

A Nurse Performance Instrument (NPI) was developed to evaluate nurses' perceptions of their performance. From a review of related existing tools (Schwirian 1978, Bertram *et al.* 1990, 1992, Battersby & Hemmings 1991, Garland 1996, Lerner *et al.* 2001), 29 potential items were included, then sent to the staff and Board of Directors of the VNA for expert review of the appropriateness of the content, readability, clarity of items and clarity of instructions. Through discussion, the research team (including nurses from the VNA) removed redundant items and those that were related to specific clinical tasks. Nine items were maintained that relate to aspects of mental, physical and general performance during nurse work tasks (see Table 3), all of which used a six-point response scale (ranging from 1 = strongly disagree, to 6 = strongly agree. The final version was reviewed and supported with respect to face validity by two RNs from the VNA. Items 1, 2, 5, 7 and 9 were reverse coded (higher scores indicating higher performance).

Ethical considerations

The local Institutional Review Board approved the study, and participants were informed about the purpose of the research and confidentiality procedures in the online survey.

Data analysis

Internal consistency of all subscales in the SOFI, FAS and OFER, and for all items in the NPI was assessed using Cronbach's alpha. All measures were tested for normality using histograms and the Shapiro–Wilk's statistic. For non-normally distributed measures, transformations were attempted. Several of the fatigue measures were found to have a non-normal distribution of residuals and Box–Cox transformations were performed to achieve normality for the F-RSQ mental and physical measures, the FAS and the OFER acute scores (all summary results are given in the original units).

Fatigue levels

Paired two-sided *t*-tests were used to identify differences between mental, physical and total fatigue levels from the SOFI; mental and physical fatigue levels from the F-RSQ; and between acute and chronic fatigue states from the OFER.

Relationships between perceived fatigue and performance

Relationships among perceived mental, physical and total fatigue levels, fatigue states (acute and chronic), and performance were examined using nonparametric correlation analyses (Spearman's r_S). Pairwise deletion was used for missing data.

Differences in fatigue levels across demographic and work environment variables

Differences in fatigue measures across demographic and work organizational variables were examined using a multivariate analysis of variance (MANOVA) of the SOFI, F-RSQ, FAS and OFER fatigue measures. Univariate analyses of variance (ANOVAs) and Tukey's *post hoc* comparisons were performed on all statistically significant factors where relevant. The Bonferroni method was used to control for type 1 error rates in these multiple comparisons and they were considered statistically significant at the $P < 0.007$ level. All statistical tests were performed in SAS 9.2 (SAS Institute Inc., Cary, NC, USA) and were considered statistically significant when $P < 0.05$ (unless otherwise specified).

Results

A total of 1006 RNs completed some portion of the survey set; of these, 745 completed the entire survey. Most respondents were female (94·2%), Caucasian (85·9%) and married (67·8%). Most classified their work environment as an acute care setting (80·5%) and over half (51·7%) reported working a standard daytime shift. More than one-third (38%) of the respondents indicated working >40 hours per week at their nursing job, with over half (57·7%) working >11 hours per shift on average. Additional demographic characteristics and a summary of the work environment variables for the survey sample are included in Table 1.

Fatigue levels

Summary statistics for the fatigue measures are presented in Table 2. Cronbach's alpha values ranged from 0·72 to 0·91, indicating that all fatigue measures had acceptable or better

Table 1 Demographic characteristics of sample and reported aspects of the work environment

	n	%		n	%
Age (years)			Years as RN		
< 20	1	0·1	< 1	68	7·0
21–30	189	19·0	1–5	171	17·5
31–40	172	17·3	6–10	134	13·7
41–50	282	28·3	11–15	101	10·3
51–60	306	30·8	16–20	110	11·3
> 60	45	4·5	21–25	125	12·8
			> 25	268	27·4
Ethnicity			Work setting		
African-American	63	6·4	Acute care hospital	797	80·5
Asian-American	16	1·6	Psychiatric facility	84	8·5
Caucasian	851	85·9	Doctor's office/public health clinic	9	0·9
Foreign National	11	1·1	Educational setting	22	2·2
Hispanic	18	1·8	Long-term care	13	1·3
Multiracial	9	0·9	Patient homes	5	0·5
Native American	5	0·5	Correctional facility	2	0·2
Native Hawaiian or other Pacific Islander	2	0·2	Other	58	5·9
Other	16	1·6			
Marital status			Years in current work setting		
Single	190	19·2	< 1	103	10·4
Married	669	67·7	1–5	366	37·0
Divorced or separated	110	11·1	6–10	197	19·9
Other	19	1·9	11–15	95	9·6
			16–20	94	9·5
			21–25	52	5·3
			> 25	82	8·3
Number of dependents			Work time on direct patient care		
0	400	40·5	76–100%	487	49·7
1–2	412	41·7	51–75%	182	18·6
3–4	161	16·3	26–50%	102	10·4
> 4	15	1·5	1–25%	130	13·3
			No patient care	79	8·1
Hours of sleep per night			Primary work schedule		
> 9	9	0·9	Regular daytime shift	513	51·7
8–9	81	8·2	Regular night shift	175	17·6
7–8	233	23·5	Regular evening shift	21	2·1
6–7	387	39·1	2 shift rotation – days/evenings	60	6·0
5–6	246	24·8	3 shift rotation	54	5·4
< 5	35	3·5	Irregular arranged by employer	43	4·3
			Irregular arranged by employee	75	7·6
			Other	52	5·2
Highest educational degree			Usual shift length (hours)		
2 year associates	247	25·2	< 8	20	2·0
3 year degree	61	6·2	8–9	230	23·2
4 year baccalaureate	426	43·4	9–10	109	11·0
Masters	193	19·7	10–11	61	6·1
PhD	5	0·5	11–12	323	32·6
Other	49	5·0	> 12	249	25·1

internal consistency (Nunnaly 1978). For the SOFI, paired *t*-tests indicated that the total fatigue dimension (lack of energy) was significantly higher than the physical exertion (t_{868} = 60·05, P < 0·0001), physical discomfort (t_{870} = 30·05, P < 0·0001) and lack of motivation (t_{869} = 42·15, P < 0·0001) dimensions. Mental fatigue (lack of motivation) levels in the SOFI were significantly higher than the physical exertion dimension of physical fatigue (t_{868} = 15·39, P < 0·0001), but significantly lower than the physical discomfort dimension (t_{869} = 15·04, P < 0·0001). Mental

Table 2 Summary of fatigue scale results

Measure	n	Score range	Mean	SD	Cronbach's alpha
SOFI					
Physical exertion	881	0–6	1·17	1·24	0·76
Physical discomfort			2·85	1·49	0·80
Lack of motivation			2·01	1·56	0·89
Lack of energy			4·20	1·45	0·88
F-RSQ					
Physical	854	0–100	27·22	20·47	n/a
Mental			36·81	26·14	n/a
FAS	879	0–5	2·42	0·52	0·72
OFER					
Chronic fatigue	874	0–100	50·07	27·74	0·91
Acute fatigue			65·55	22·06	0·87
Intershift recovery			50·1	23·61	0·87

fatigue levels on the F-RSQ were also significantly higher than physical fatigue levels ($t_{875} = 11·05$, $P < 0·0001$). For the OFER scale, nurses perceived significantly higher levels of acute fatigue than chronic fatigue ($t_{869} = 17·5$, $P < 0·0001$).

Relationships between perceived fatigue and performance

Cronbach's alpha for the entire NPI was 0·80, and Cronbach's coefficient alpha with deleted variable values for each of the nine items ranging from 0·77 to 0·80 (Table 3), indicating acceptable internal consistency (Nunnaly 1978) for this new instrument. Performance levels were highest for specific tasks or safety guidelines (items 3, 4, 6 and 8). Scores were lowest for broader performance changes because of changes in mental or physical energy levels (items 1, 5 and 7).

Most performance measures from the NPI were significantly and negatively correlated with all fatigue measures (Table 4). NPI item 3 (regarding the 'five rights' principal, see Table 3) was the only item that was not significantly negatively correlated with all fatigue measures; it was not significantly correlated with SOFI physical discomfort, SOFI physical exertion or FAS.

Differences in fatigue levels across demographic and work environment variables

MANOVA indicated that fatigue levels were significantly different between levels of several demographic and work environment variables. Univariate ANOVAS performed on statistically significant factors indicated that physical fatigue levels from the SOFI physical discomfort dimension differed across work settings ($F_{7,785} = 3·53$, $P = 0·0010$), hours worked per week ($F_{4,785} = 3·89$, $P = 0·0039$) and hours of sleep per night ($F_{5,785} = 4·19$, $P = 0·0009$), while the SOFI physical exertion dimension differed across hours worked per week ($F_{4,785} = 5·71$, $P = 0·0002$), and hours of sleep per night ($F_{5,785} = 3·80$, $P = 0·0021$). *Post hoc* comparisons showed that participants working in long-term care facilities had higher physical exertion levels than those working in acute care hospitals or doctor's offices and higher physical

Table 3 Results from questions comprising the Nursing Performance Instrument ($N = 799$)

Item	Prompt	Mean†	SD	Cronbach's alpha with deleted variables
1	During a work shift, changes in my muscle strength, endurance or physical energy affect my ability to perform physical tasks associated with my job (e.g. carry items, perform patient handling tasks, walk/drive from patient to patient, etc.)	3·63	1·50	0·79
2	I sometimes find it necessary to take short-cuts in patient care	4·02	1·46	0·77
3	I always apply the '5 Rights' principle when administering medications	5·03	1·13	0·79
4	Throughout a work shift I am able to perform fine motor tasks (e.g. inserting an IV, catheter insertion, medication preparation, etc.) without difficulty	4·98	0·97	0·80
5	During a work shift, changes in my concentration or alertness affect my ability to perform patient monitoring, medication administration and/or documentation tasks	3·78	1·47	0·77
6	I am always able to carry out safe nursing practice	4·66	1·17	0·78
7	During a work shift, changes in my mood, mental energy or attentiveness affect my ability to communicate clearly and effectively (e.g. express my opinions, understand what others are saying, etc.) with other nurses, physicians, clinicians, patients or family members	3·33	1·43	0·78
8	I always follow existing facility or organizational guidelines for safe patient handling (e.g. use of lift devices, two person lifts, etc.)	4·37	1·30	0·79
9	I am sometimes forced to modify my standards to get the work done	3·65	1·51	0·78

†Item response scale ranged from 1 (strongly disagree) to 6 (strongly agree). Scores from items 1, 2, 5, 7 and 9 were reverse coded so that higher scores indicate higher performance.

Table 4 Correlations (r_S) among fatigue and performance measures

	SOFI				F-RSQ			OFER		
	Physical exertion	Physical discomfort	Lack of motivation	Lack of energy	Physical	Mental	FAS	Chronic fatigue	Acute fatigue	Intershift recovery
NPI 1	−0·29***	−0·45***	−0·31***	−0·38***	−0·37***	−0·35***	−0·28***	−0·37***	−0·37***	0·37***
NPI 2	−0·11**	−0·10**	−0·24***	−0·24***	−0·12***	−0·23***	−0·14***	−0·31***	−0·27***	0·20***
NPI 3	−0·02	−0·03	−0·20***	−0·10**	−0·07*	−0·17***	−0·07	−0·09*	−0·13***	0·11**
NPI 4	−0·14***	−0·16***	−0·15***	−0·09**	−0·15***	−0·20***	−0·12**	−0·17***	−0·18***	0·23***
NPI 5	−0·17***	−0·25***	−0·38***	−0·31***	−0·20***	−0·42***	−0·22***	−0·29***	−0·34***	0·30***
NPI 6	−0·12***	−0·15***	−0·27***	−0·21***	−0·16***	−0·24***	−0·16***	−0·23***	−0·26***	0·24***
NPI 7	−0·20***	−0·26***	−0·38***	−0·33***	−0·21***	−0·42***	−0·26***	−0·34***	−0·35***	0·33***
NPI 8	−0·09*	−0·06	−0·23***	−0·11**	−0·12**	−0·18***	−0·12***	−0·15***	−0·16***	0·12***
NPI 9	−0·19***	−0·18***	−0·25***	−0·22***	−0·17***	−0·21***	−0·17***	−0·37***	−0·29***	0·22***

***$P < 0{\cdot}001$; **$P < 0{\cdot}01$; *$P < 0{\cdot}05$; obtained from Spearman's rank correlation (Prob > $|r_S|$).

discomfort levels than those working in patient homes. Nurses working in long-term care facilities reported the highest levels on the SOFI physical discomfort and physical exertion scales (2·40 and 4·00), while nurses working in patient homes and correctional facilities reported the lowest levels (0·25 and 1·38; and 1·25 and 1 respectively). Furthermore, participants who worked >60 hours per week had higher SOFI physical discomfort and physical exertion levels than those working ≤40 hours per week. SOFI physical fatigue levels (both physical exertion and physical discomfort) were also higher for participants with ≥6 hours of sleep per night compared to 5–6 hours of sleep per night.

For the F-RSQ, ANOVAs indicated that physical fatigue levels differed across hours of sleep per night ($F_{5,822} = 4{\cdot}76$, $P = 0{\cdot}001$), work schedules ($F_{7,822} = 3{\cdot}58$, $P = 0{\cdot}002$) and shift lengths ($F_{5,822} = 4{\cdot}84$, $P < 0{\cdot}001$). From Tukey's *post hoc* tests, participants with 7–8 or 8–9 hours of sleep per night were significantly less physically fatigued than those with 5–6 or <5 hours of sleep per night. Nurses working a regular night schedule had F-RSQ Physical scores that were lower than those working a 'regular evening' schedule, and lower than those working 'rotation days/evenings' schedules (Figure 1). Respondents working 8–9 or 9–10 hour shifts had lower F-RSQ scores than those working 10–11 or >12 hour shifts.

Reported mental fatigue (from the F-RSQ) significantly differed with years in current work setting ($F_{6,817} = 3{\cdot}70$, $P = 0{\cdot}002$) and work schedule ($F_{7,817} = 4{\cdot}79$, $P < 0{\cdot}001$). Nurses working a regular night schedule had lower scores than those working 'regular evening' or 'rotation days/evenings' schedules (Figure 1). Furthermore, nurses working 'rotation all shifts' schedules had lower F-RSQ Mental scores than those working 'regular evening' or 'rotation days/evenings' schedules.

The SOFI lack of energy measure of total fatigue was significantly different across ethnicities ($F_{8,785} = 3{\cdot}57$, $P = 0{\cdot}0004$) and work schedule ($F_{7,785} = 4{\cdot}03$, $P = 0{\cdot}0002$). Ethnicity ($F_{8,811} = 3{\cdot}00$, $P = 0{\cdot}002$) and hours of sleep per

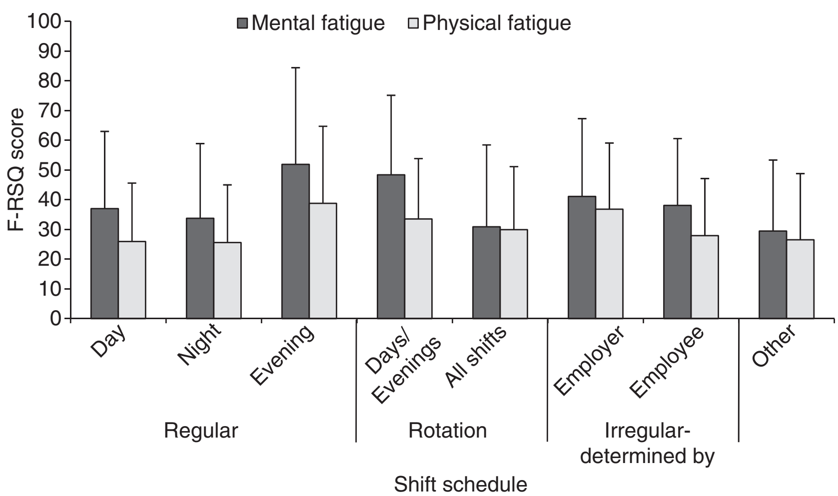

Figure 1 Differences in F-RSQ mental and physical scores (higher = increased fatigue) across work schedules. Here, and in the remaining figures, error bars indicate standard deviations.

night ($F_{5,811}$ = 6·86, P < 0·001) were associated with statistically significant differences in total fatigue, measured by the FAS. Participants who slept 7–9 hours per night had lower FAS total fatigue levels than those who slept <6 hours per night. There were also statistically significant differences between 6–7 and <5 hours of sleep per night; in all cases, less sleep led to higher FAS scores.

Finally, several factors were associated with differences in chronic fatigue levels: hours of sleep per night ($F_{5,808}$ = 4·01, P = 0·001), total hours worked per week ($F_{4,808}$ = 3·51, P = 0·007) and work schedule ($F_{4,808}$ = 3·51, P = 0·005). By contrast, acute fatigue was significantly different across hours of sleep per night ($F_{5,808}$ = 4·32, P < 0·001), work schedule ($F_{7,808}$ = 3·54, P < 0·001) and shift length ($F_{5,808}$ = 4·75, P < 0·001). For acute and chronic fatigue, participants who slept 6–9 hours per night had lower scores than those who slept 5–6 hours per night. Participants who worked <20 hours per week had lower chronic fatigue scores than those who worked 41–80 hours per week. Acute fatigue scores were significantly lower (Figure 2) for: regular daytime and regular night shifts compared with regular evening, for regular night compared with rotation between days/evenings, for irregular shift schedules determined by the employee or rotation across all shifts compared with regular evening and for rotation across all shifts compared with rotation between days/evenings.

Discussion

Study sample

The current sample approximates that reported in the 2001 American Nurses Association Health and Safety Survey (ANA, 2001), the 2000 National Sample Survey of Registered Nurses (Spratley *et al*., 2001) and the 2004 National Sample Survey of Registered Nurses (Steiger *et al.* 2004, Trinkoff *et al.* 2006). Thus, the current sample is considered reasonably representative of the larger population of RNs in the USA. Despite this, the current results may not be generalizable to other nursing groups (e.g. LPNs, NAs) or other healthcare worker populations, as work tasks vary substantially across occupations and job titles. Furthermore, it was not possible to ensure that there were no repeated participants in the sample.

Mental, physical and total fatigue levels

Nurses worldwide have reported high levels of fatigue and listed fatigue as one of the major factors contributing to a decision to leave the profession (Estryn-Behar *et al.* 1990, Zboril-Benson 2002, Winwood *et al.* 2006b). Nurses in the current study reported levels of mental, physical and total fatigue that were quite high (Table 2). Nurses here perceived total fatigue (4·2/6) to be higher than either mental (2·0) or physical fatigue (1·2), as measured using the SOFI. They also perceived mental fatigue to be higher than physical fatigue for both the SOFI and the F-RSQ, although their physical discomfort levels (2·9/6) were higher than their perceived levels of mental fatigue (2·0) on the SOFI. Soh and Crumpton (1996) also found that nurses reported higher levels of mental fatigue than physical fatigue (measured by the F-RSQ) over the course of an 8-hour work shift.

In considering the differences between mental and physical fatigue levels, it is important to note that mental fatigue levels may be influenced by both mental and emotional demands in nursing work tasks. Emotional demands have been included

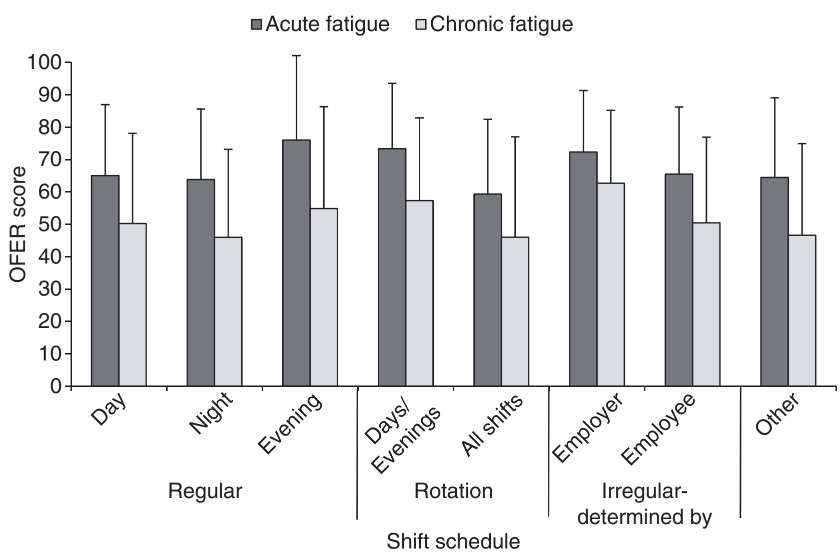

Figure 2 OFER acute and chronic fatigue scores across work schedules (higher = increased fatigue).

as factors in mental workload models in healthcare workers (Bertram *et al.* 1990) and may contribute to the perceptions of mental fatigue. Thus, the higher levels of mental fatigue compared with physical fatigue in nurses may be attributable to both mental and emotional demands prevalent across nursing work environments.

Furthermore, although nursing work is often thought of as primarily mentally vs. physically demanding, and is consistent with the higher perceived levels of mental vs. physical fatigue, the physical demands associated with nursing are substantial and should not be ignored (Trinkoff *et al.* 2001b). Additionally, the higher levels of physical discomfort compared with mental fatigue or physical exertion in this study is deserving of further attention given the relatively high rates of overexertion and occupational injuries among this population (Stubbs *et al.* 1983, Punnett 1987, Bureau of Labor Statistics 2005). Finally, as we could not control when nurses completed the surveys relative to a work shift, there may have been recovery or recall biases in reported fatigue levels, particularly for perceived physical demands (Torgen *et al.* 1999).

Acute and chronic fatigue states

Nurses indicated that they were more acutely than chronically fatigued as hypothesized, and acute fatigue is generally considered more common occupationally (Aaronson *et al.* 2003, Winwood *et al.* 2005). Although nurses in this study reported higher levels of acute fatigue than chronic fatigue (15% higher), the chronic fatigue level (~50%) can be classified as 'moderate' and is comparable with levels found among nurses in Australia (Winwood *et al.* 2005, 2006b). Furthermore, acute and chronic fatigue cannot be considered in isolation from one another. Chronic fatigue among workers is a consequence of high levels of acute fatigue coupled with insufficient recovery between work shifts. Compared with acute fatigue, chronic fatigue is associated with more substantial consequences on worker health, well-being and work performance (Winwood *et al.* 2005). Thus, the moderate level of chronic fatigue reported in this study, coupled with the increasing prevalence of extended work shifts (Trinkoff *et al.* 2006, Winwood *et al.* 2006b), may have implications for both nurse and patient safety.

Fatigue and performance

Fatigue dimensions and states were correlated with performance measures, further supporting the role of fatigue in nurse performance. Mental fatigue measures tended to have higher negative correlations with the performance measures than did either physical fatigue or total fatigue. Specifically, mental fatigue measures (SOFI LoM and F-RSQ Mental) were most strongly negatively correlated with NPI 5 and NPI 7, which relate to changes in concentration, mood, and mental energy, and the implications for patient monitoring, medication administration and documentation tasks. These results compliment existing evidence that, in healthcare workers, performance on tasks requiring vigilance or attention to detail, or which are long in duration, may be particularly susceptible to fatigue-related consequences (Krueger 1994, Owens 2001, Howard *et al.* 2002). Physical fatigue measures, in contrast, were most strongly negatively correlated with NPI 1, which relates to muscle strength, endurance and physical energy abilities relative to physical nursing tasks. Across all fatigue dimensions, the lowest negative correlations were with NPI 3 and NPI 8. These two items related to particular guidelines in nursing practice. Thus, performance guidelines that specifically govern clinical practice may, in some instances, mitigate the negative associations between perceived fatigue and performance.

Acute fatigue and chronic fatigue had comparable levels of correlation with all NPI items. However, chronic fatigue was more strongly negatively correlated with NPI 2 and NPI 9, both of which relate to taking shortcuts or modifying standards to get work done. Chronic fatigue has been linked to declining interest and reduced motivation in work (Winwood *et al.* 2006a), again highlighting the importance of continuing to measure chronic fatigue levels in nurses. When considering the relationships between perceived fatigue and performance in the current study, it is important to acknowledge that the study was cross-sectional. Thus the directionality of relationships between fatigue and performance cannot be determined.

Differences in fatigue levels across demographic and work environment variables

There were differences in perceived levels of physical, mental and total fatigue, and also chronic and acute fatigue states for several of the demographic variables. Physical and total fatigue levels differed, as did chronic and acute fatigue levels, with reported average hours of sleep per night. Hours of sleep per night were not, however, related to reported mental fatigue levels, either in the SOFI or the F-RSQ measures. Thus, although RNs reported relatively high levels of mental fatigue, these perceptions were not related to reported hours of sleep. Sleep quality, although, was not considered separately from sleep hours, and the former has been suggested as an important predictor of occupational fatigue (Akerstedt *et al.* 2004).

Relationships between work environment variables and fatigue dimensions are critical as these variables can, in theory, be influenced through workplace design or controls to

What is already known about this topic

- Medical errors and worker injuries are serious challenges in the healthcare industry.
- Fatigue has been linked to nurse injuries, nurse satisfaction and patient safety.
- Nurses frequently perform both physically and mentally demanding tasks, and are exposed to long working hours with little recovery time between shifts.

What this paper adds

- Registered nurses, from a range of healthcare work environments, report higher levels of mental than physical fatigue, and moderate levels of both acute and chronic fatigue.
- Perceptions of fatigue dimensions and states in registered nurses are inversely correlated with perceptions of performance.
- Work environment variables (e.g. shift length, shift schedule, hours worked per week) are strongly associated with perceived levels of fatigue in registered nurses.

Implications for practice and/or policy

- Physical, mental and total fatigue dimensions, and also both acute and chronic fatigue states, should be considered when quantifying fatigue levels in registered nurses.
- Performance guidelines that specifically govern clinical practice may, in some instances, mitigate the negative relationships between perceived fatigue and performance.
- Hours worked per week, shift length and shift schedule are associated with differences in fatigue levels; nurse managers should consider these variables when designing nursing work environments and schedules.

reduce fatigue levels. Recent changes in the healthcare industry, including worker shortages and efforts to reduce costs, have also led to increases in extended work hours for nurses, and this has important implications for both nurse and patient safety. Extended work hours have been linked to an increased likelihood of injuries, increased fatigue, decreases in performance and reaction time, and increases in unhealthy life behaviours (Trinkoff *et al.* 2006). Nurses working shifts of 9 or 12 hours have reported higher fatigue levels and lower performance compared with those working 8-hour shifts (Josten *et al.* 2003). Furthermore, nurses working shifts exceeding 12·5 hours are more than three times more likely to commit an error than nurses who work shorter shifts (Narumi *et al.* 1999, Rogers 2004).

Here, longer shift lengths and increased hours worked per week were associated with higher levels of physical and total fatigue, and also acute and chronic fatigue. There was no statistically significant difference in mental fatigue, however, across shift lengths or hours worked per week. Akerstedt (2000) also found that work hours and overtime were not statistically significant predictors of mental fatigue. While some in the nursing and healthcare communities have expressed support for longer work shifts (Underwood 1975, Ganong *et al.* 1976, Gillespie & Curzio 1996), the statistically significant negative relationship between longer work hours and fatigue levels identified in both the current and previous studies suggests a continuing cause for concern.

Shift schedule, in contrast, was associated with differences in all fatigue dimensions and also chronic and acute fatigue state levels (Figures 1 and 2). The influences of shift schedules on fatigue levels, performance and well-being in nurses and other healthcare workers has been well documented (Gold *et al.* 1992, Lindborg & Davidhizar 1993, Muecke 2005). Night shifts and rotating shift patterns, in particular, have both been associated with increasing fatigue levels and insufficient recovery from work between shits (Winwood *et al.* 2006b). The nature of health care and many nursing positions, however, prohibits a complete avoidance of evening/night shifts. There are some shift scheduling parameters (e.g. worker involvement in schedule selection, shift length and rotation patterns), although, that are potentially flexible and that could reduce negative fatigue-, health- or performance-related consequences in this population (Josten *et al.* 2003, Winwood *et al.* 2006b).

Conclusions

Nurses (RNs) reported higher levels of mental than physical fatigue and higher levels of acute than chronic fatigue. Statistically significant negative correlations were evident between perceived levels of fatigue and performance across all fatigue dimensions and states. Contemporary challenges in healthcare systems, such as nursing shortages, increased patient loads and decreased resources, continue to place higher demands on the workers. Hence, understanding the relationships between the work environment, fatigue and performance is critical. Future work is needed to build on the associations between fatigue and performance in this study and evaluate causal implications of fatigue on performance. The potential mitigating role of specific nursing practice guidelines on the negative effects of fatigue on performance should also be further explored. Additionally, the moderate levels of chronic fatigue reported here deserve further attention as discussions related to work-hour limitation and shift-scheduling policies proceed in the nursing community. Demographic and work environment variables (e.g. shift length, shift schedule, hours of sleep per night and years of experience in a given work setting) had important effects on perceived levels of fatigue in RNs. Thus, nurse managers and industrial engineers should consider these variables when designing nurse work environments and schedules to avoid excessive fatigue levels. Further work is needed to consider these variables simultaneously. Specifically, interactions between shift length, shift schedule and resulting fatigue levels should be evaluated, as these variables are aspects of the work environment that can be manipulated, and may especially have effects on increasing chronic fatigue levels and associated consequences for both nurse and patient safety.

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Conflict of interest

No conflict of interest has been declared by the authors.

Author contributions

LMB and MAN were responsible for the study conception and design. LMB performed the data collection. LMB performed the data analysis. LMB was responsible for the drafting of the manuscript. LMB and MAN made critical revisions to the paper for important intellectual content. MAN provided statistical expertise. MAN provided administrative, technical or material support. MAN supervised the study.

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Driver sitting comfort and discomfort (part II): Relationships with and prediction from interface pressure

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Abstract

Pressure at the driver–seat interface has been used as an objective method to assess seat design, yet existing evidence regarding its efficacy is mixed. The current study examined associations between three subjective ratings (overall, comfort, and discomfort) and 36 measures describing driver–seat interface pressure, and identified pressure level, contact area, and ratio (local to global) variables that could be effectively used to improve subjective responses. Each of 27 participants was involved in six separate driving sessions which included combinations of two seats (from vehicles ranked high and low on overall comfort), two vehicle classes (sedan and SUV), and two driving venues (lab-based and field). Several pressure variables were identified as more effective for assessing sitting comfort and discomfort across a range of individual statures. Based on the results, specific approaches are recommended to improve the sitting experience: (1) lower pressure ratios at the buttocks and higher pressure ratios at the upper and lower back; and (2) balanced pressure between the bilateral buttocks, and between the lower and upper body. Finally, separate analyses supported that human–seat interface pressure was more strongly related with overall and comfort ratings than with discomfort ratings.

Relevance to industry

Several interface pressure variables were identified that showed associations with subjective responses during sitting. Use of these measures is suggested to improve the quality of car seats.

Keywords: Interface pressure; Sitting comfort; Driving posture; Packaging

1. Introduction

A comfortable seat plays an important (though not exclusive) role in the perception of a vehicle's overall quality. As a way of meeting customers' increased need for and expectation of vehicle comfort, car makers have been seeking more effective ways to improve car seats. It is hoped that improving seat comfort will distinguish their product from others in the competitive automotive market. Subjective ratings and objective measures (e.g., joint angles, pressure, electromyography) have been used to determine how to enhance sitting comfort and discomfort (de Looze et al., 2003). Among other factors, a driver's sitting comfort and discomfort have been shown to be influenced by whether there is adequate support for preferred driving postures (Reed et al., 1994), even distribution of contact pressure (Helander et al., 1987; Sanders and McCormick, 1987), and mitigated vibration (Johnson and Neve, 2001). Each of these should be provided by the driver's seat and can be described in terms of driver–seat interface pressure.

Such pressure data were regarded by de Looze et al. (2003) as an objective measure having a clear association with subjective ratings. Previous studies have shown that preferred pressure levels are different between body parts as well as between anthropometric groups (Dunk and Callaghan, 2005; Kamijo et al., 1982; Kolich, 2004; Oudenhuijzen et al., 2003), and that there are associations between interface pressure and sitting discomfort. On the other hand, some studies have failed to find this association. For example, Gyi (1996) indicated that sole use of

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interface pressure was not successful in predicting car seat discomfort. Therefore, use of different types of pressure data, and quantifying comfort instead of discomfort (Kyung et al., in press), may be more successful at identifying associations between pressure and human responses. If so, such associations would facilitate determining seat design and evaluation criteria for diverse groups of people in terms of pressure levels.

As psychological constructs, similar to 'fatigue' or 'effort', comfort and discomfort have been suggested to require treatment as different and complementary entities in ergonomic evaluations and interventions (Sauter et al., 2005). Zhang et al. (1996) found that comfort and discomfort are orthogonal, and therefore should be treated independently. Consistent with the orthogonality between comfort and discomfort, the present study incorporated a separate scale for each of these, and aimed at finding their relationships with objective measures (i.e., interface pressure). The longer-term goal was obtaining effective methods, using pressure variables, for ergonomic intervention and evaluation of sitting comfort and discomfort in driving workspaces.

Precise quantification of in-vehicle sitting comfort/discomfort requires that seat and package geometries, driving postures and visual demands are set close to actual driving situations. Troup (1978) showed that the car seat is one major factor affecting a driver's comfort, and can play a positive role in prevention of back pain by alleviating vibration and road shock. Rebiffé (1969), on the other hand, indicated that ergonomic vehicle packaging, specifically harmonic layout of relevant parts, is more important for overall comfort than the seat itself. Anshel (2005) indicated that visual information in human–machine systems was so dominant that its deficiency could often result in awkward body postures. Driving involves high visual demands (Wierwille and Tijerina, 1996), which can thus change the driving posture and result in postural discomfort (Pheasant, 1992). Seat and package geometries and driving postures, in turn, likely influence interface pressure distributions.

Besides ensuring realistic conditions, in terms of seat, posture, task, and environment, which are necessary (especially in a lab-based study) for their contextual effect on the human response (Annett, 2002), a safety belt should also be incorporated for the same reason. During the past 5 years (2000–2004), safety belt usage rates in the US have risen from 72% to 81% (BTS, 2006). Thus, to better represent driving conditions, a safety belt should be worn during an experiment. Further, without a proper restraining system, participants are more likely to slip forward and to be in (more) slouched postures, which can result in pressure changes.

In general, people have more limited freedom to change their postures in car seats than in traditional chairs. For reasons of musculoskeletal health, however, postural movement is essential. Akerbloom (1948) noted that a comfortable seat should accommodate postural changes. Jenny et al. (2001) stated that facilitation of nutrition and relief of muscle fatigue come from postural movement. Likewise, Dhingra et al. (2003) suggested that changes in body position should be allowed to relieve pressure on muscle groups and to relax them. Such postural change for comfort will also be reflected in pressure data.

Different pressure levels between bilateral lower body parts in a driving posture are expected due to the different task and postural requirements placed on each lower extremity. For example, the right foot, used to control pedals, is required to take more restricted postures with less consistent support, while the left foot, unless a clutch pedal is considered, is relatively free and consistently supported by the car floor or the foot rest. Due to this, the left foot (and the left lower limb) might be involved more dominantly in postural balance, which would result in a bilaterally asymmetric posture and pressure. Indeed, the preferred driving posture has been shown to be asymmetric (Hanson et al., 2006).

Short- and long-term sitting comfort/discomfort need to be distinguished. Sitting discomfort increases over time while sitting comfort tends to remain constant (Helander and Zhang, 1997). Increased discomfort seems largely associated with fatigue, which can result from 1 h of driving (Uenishi et al., 2002). Some authors have suggested long-term test durations for the assessment of seat discomfort. For example, Gyi and Porter (1999) stated that at least 2 h of testing was required to clearly assess discomfort, which seems mainly focused on measuring fatigue in seated postures. Fatigue in sitting, however, could be simply due to "the passage of time" (Helander and Zhang, 1997), and not necessarily due to the seat design. Further, fatigue in vehicles has been shown to be affected by multiple other sources such as temperature, air quality, noise (Gameiro da Silva, 2002), and circadian factors (Brown, 1994; Moore-Ede et al., 2003; Van Dongen and Dinges, 2000). Use of interface pressure does not account for these factors, but rather accounts for the seat's support and pressure distribution characteristics and postural changes. Therefore, in using pressure data for assessment of sitting comfort/discomfort, a method is required that can determine their levels within a relatively short period of time. Moreover, a compiled version of the 1990 Nationwide Personal Transportation Survey (NPTS) data by Reed and Massie (1996) showed that about 82% of trips taken in the US were $\leqslant$20 min. Hence, short-term driving is also more representative of actual driving patterns than long-term driving.

In contrast, more extended durations have been generally used when investigating sitting discomfort (largely due to fatigue). For example, Uenishi et al. (2002) investigated driver fatigue in a lab-based environment and observed its occurrence in 1 h. Gyi and Porter (1999) recommended at least 2 h of testing to clearly assess discomfort (fatigue). As already noted, fatigue in seated postures has diverse contributing factors, and can actually result from other sources than the seat. Even when the seat is a major factor, other aspects, rather than the seat's function in providing support and distribution of body pressure, could be the major sources of any unpleasant feeling in sitting. These other aspects include the seat's aesthetics (color, texture, leather cover) and functionality (easy-to-use controls, lumbar support, power seat, massage seat, and evaporation characteristics).

Interface pressure is commonly used as an objective measure in the study of seat discomfort, but evidence suggests that more careful consideration is needed for proper use given its limitations. Several problems can occur when using pressure mats for extended periods. The first is creep, defined as a measurement drift under a constant load, and the second is hysteresis, which is apparent as a different force–displacement pattern between loading and unloading. In fact, Fay and Brienza (2000) suggested that creep and hysteresis could have been confounding variables in the work of Gyi and Porter (1999), leading to their failure to identify "a clear, simple and consistent relationship between interface pressure and driving discomfort" (Fay and Brienza, 2000, p. 2255). In addition, a seat's sweat evaporation characteristic can be substantially altered, particularly if pressure mats are used (as they should) during the entire period of driving. Thus, with increasing sitting time, individuals are more likely to feel uncomfortable in terms of "stickiness caused by un-evaporated sweat" (Parsons, 2000), which in turn adversely affects their discomfort ratings. Comfort ratings may also be affected, as sitting comfort is significantly correlated with sitting discomfort (Kyung et al., in press).

In addition, ambient factors (e.g., noise, light, and air temperature) not accounted for by interface pressure can affect subjective responses. Such factors are usually set to predefined levels, yet the potential for confounding may still exist. For example, Karjalainen (2007) observed significant differences in thermal comfort and temperature preference between gender groups. Therefore, a preferred method is to allow participants to select the levels of any controllable ambient factors according to their preferences.

Aside from such technical issues, the means by which pressure data are integrated into subjective responses remains unclear. Different weightings of pressure data at local body parts may be used by individuals in determining global levels of comfort and discomfort. From a macroview, Humphreys (2005) investigated combined comfort indices of the indoor environment, consisting of warmth, lighting, humidity and air quality. Results showed that the importance of each component was different during the "subjective averaging process" (Humphreys, 2005, p. 319) used in determining an overall satisfaction level, and also that there existed different averaging processes between cultural groups. Similarly, it was postulated by the current authors that, from a microview, while all body parts contacting the seat play a role in determining whole body comfort and discomfort, each local body part and the associated interface pressure are weighted differently in the integration/decision process. Therefore, it was investigated here whether there were more dominant body parts (and corresponding pressure variables) in this process, and whether there was an ideal ratio in terms of pressure distribution among thighs, buttocks and back that could yield improved sitting comfort and discomfort.

In summary, the primary objective of this study was to investigate the associations between interface pressure and subjective ratings of short-term sitting comfort/discomfort, in order to determine the types and derivates of pressure data that could be substituted for, and hence predict, comfort and/or discomfort. In addition, comparisons were made between two groups of people that had different levels of reported sitting comfort and discomfort. Specific objectives were: (1) to determine the effectiveness of a comprehensive set of 36 interface pressure variables (pressure levels, contact areas, and ratios of local to global pressure). This effectiveness was determined for assessing, predicting and improving the sitting experience in terms of comfort, discomfort and/or overall ratings across a range of individual statures; (2) to identify specific pressure variables most related to a better sitting experience; and (3) to investigate effects of stature, vehicle class (sedan and SUV), seat, and venue (laboratory and field settings) on the set of variables.

2. Methods

2.1. Overview of experiment and participants

Data were obtained from a study of perceived comfort/discomfort involving both lab-based (simulated) and actual (field) driving venues. Details on the criteria for selection of participants and experimental vehicles/seats, the subjective rating scales, and the experimental design have been provided in a companion paper (Kyung et al., in press), with only a summary given here. After providing informed consent, using procedures approved by the local IRB, each of 27 participants (aged 20–35, 12 males and 15 females, mean (SD) mass = 69.1 (13.1) kg, mean (SD) stature = 170.7 (11.7) cm) completed six short-term (15–20 min) driving sessions. Each used, in a random order, a different combination of seat, vehicle class, and driving venue (specific combination = Seat Condition). For selection of vehicles and seats, the J. D. Power and Associates' Comfort Score (J.D. Power and Associates, 2005) was used; higher- and lower-rated vehicles and their seats were selected (Kyung et al., in press). Measures of subjective responses, pressure, and posture were obtained. Additional objective measures (joint angles) were collected at the end of each session (after all subjective ratings were obtained), but are not presented here. An analysis of pressure data, and its association with subjective responses, is the focus of this report.

2.2. Variables

2.2.1. Independent variables

Two independent variables were included. Seat Condition had six levels, obtained as a subset of the combinations of two vehicle classes (sedan, S; SUV, U), two seats (S1 and S2, and U1 and U2 from higher (1) and lower (2) rated vehicles in a given vehicle class), and driving venue (lab-based,—L; field,—F). Lab-based sessions were conducted in an isolated room, using a custom-constructed driving rig (that allowed for extended adjustments of the seat and steering wheel), and with a driving scene projected in front of the participant. Field sessions were conducted over a predetermined path on local roads. The specific Seat Conditions were S1-L, S1-F, S2-L, U1-L, U1-F, and U2-L. The second independent variable was Stature, representing three groups of participants (short, middle, and tall) with respective stature ranges (percentiles of gender-mixed population; NHANES III, 1994) of 152–164 ($\leqslant$18th), 165–174, and 175–193 cm ($\geqslant$90th).

2.2.2. Dependent variables

Both subjective ratings and objective measures were obtained. Three subjective rating schemes were used, consisting of overall ratings for the whole body, and comfort and discomfort ratings for the whole body and six local body parts (Table 1). Methods used to obtain these ratings are provided in detail in the companion paper (Kyung et al., in press). Briefly, overall ratings were based on a visual analogue scale, with comfort and discomfort at the extremes, thereby measuring a mixture of comfort and discomfort. The separate comfort/discomfort scales measured only one feeling independently, using scales derived as combinations of versions developed by Borg (1990) and Corlett and Bishop (1976). These scales range from 0 to 10, and from 0 to -10, for comfort and discomfort, respectively. Separate measures of comfort and discomfort were obtained to reflect existing evidence of the orthogonality of comfort and discomfort (Sauter et al., 2005; Zhang et al., 1996) or a study which has regarded these two feelings as different entities (Hancock and Pepe, 2005). Objective measures were obtained from pressure measured at the driver–seat interface, and consisted of two groups: overall and local pressures (Table 1).

2.3. Experimental protocols

During initial seat and posture adjustments (duration $\leqslant$5 min), a pressure mat was placed on only the seat cushion and secured with masking tape (to facilitate seat adjustments). The participant was instructed to sit carefully to minimize wrinkles on the pressure mat, and then placed their right foot on the gas pedal (required) and their left foot on the foot rest (optional). Adjustments of the seat and steering wheel were made until the participant's preferred posture was found. After the participant arose from the seat, the second pressure mat was secured to the seat back. The participant sat on the seat again, wore a lap belt, and made microadjustments as desired. Room or vehicle temperature was set to the participant's preference before the driving session.

Table 1
Dependent variables

Type	Name	Area to measure
Subjective	Overall rating	Whole body
	Comfort rating	Whole body and six local body parts
	Discomfort rating	• Left/right thighs (THL/THR)
		• Left/right buttocks (BTL/BTR)
		• Upper/lower back (UB/LB)
Objective	Overall pressure	Sum of six local body part pressures
	Local pressure	Each local body part

2.4. Data collection and processing

Subjective ratings were obtained after each session, in a consistent order to minimize confusion (discomfort, comfort, and then overall ratings). Pressure data were collected continuously during the driving sessions, using two Tekscan (South Boston, MA, USA) pressure mats (5330 CONFORMat™). Each pressure mat comprised 1024 (32×32) thin (1.78 mm) resistive sensors that could easily conform to the contour of the seat, and measure up to 250 mmHg (5 PSI). Each mat had an active area of 471.4 mm $\times$ 471.4 mm, and sensor pitch was 14.73 mm (0.5 sensor/cm^2). Pressures were recorded at 0.5 Hz, the maximum possible due to hardware limitations. This sampling rate, however, was considered sufficient, as the frequency of postural changes and resultant pressure changes were not observed to occur within an order of magnitude of the sampling rate.

Pressure data from the two mats were divided into six groups (Fig. 1). Bolsters on the sides of the car seat play a role in supporting thighs, hips, and back (especially when turning), and can affect sitting comfort and discomfort (Andreoni et al., 2002). To account for this, pressure data corresponding to bolstered areas were also included in the data analysis. Contact area and contact pressure were calculated by including only data from sensors that were pressed (i.e. a positive value) at least once, and average (arithmetic mean) values were determined for the last 5 min of driving. Earlier data were excluded here, as they were 'transient' due to settling into the seat (Reed et al., 1999). Contact area and pressure values were obtained from the Movie Contact Averaging function available in the CONFORMat Research software (version 5.80c).

2.5. Data analysis

A total of 39 pressure variables were derived (Table 2): (1) the first 13 variables were related to average contact areas and ratios; (2) the second 13 variables described average contact pressures and ratios; and (3) the last 13 variables indicated average peak contact pressures and ratios. Three overall pressure variables (aSUM, avgSUM, and pkSUM) were only used to derive 18 ratio variables, and were not further analyzed.

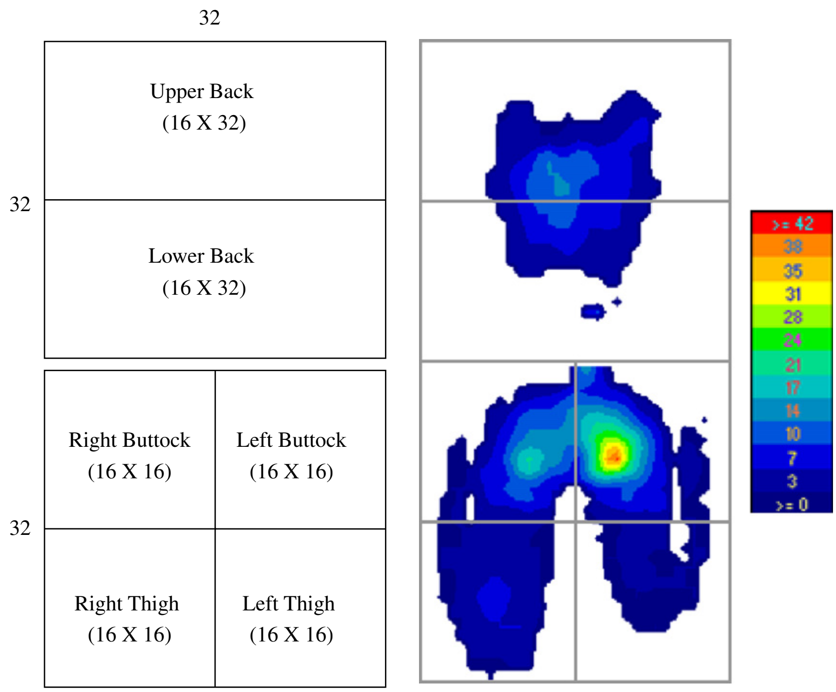

Fig. 1. Division of two pressure mats for six local body parts (left, number of sensors in parentheses; row by column) and exemplar pressure distribution (right, a higher peak pressure on left buttock).

Table 2
Pressure variables and groups

Group	Variable name and description	
Average contact area (cm^2)	aTHL (aTHR): aBTL (aBTR): aLB (aUB): aSUM:	Left (right) thigh Left (right) buttock Lower (upper) back aTHL + aTHR + aBTL + aBTR + aLB + aUB
Average contact area ratio	aTHL/aSUM , aTHR/aSUM , aBTL/aSUM, aBTR/aSUM, aLB/aSUM, aUB/aSUM	
Average contact pressure (mmHg)	avgTHL (avgTHR): avgBTL (avgBTR): avgLB (avgUB): avgSUM:	Left (right) thigh Left (right) buttock Lower (upper) back avgTHL + avgTHR + avgBTL + avgBTR + avgLB + avgUB
Average contact pressure ratio	avgTHL/avgSUM, avgTHR/avgSUM, avgBTL/avgSUM, avgBTR/avgSUM, avgLB/avgSUM, avgUB/avgSUM	
Average peak contact pressure (mmHg)	pkTHL (pkTHR): pkBTL (pkBTR): pkLB (pkUB): pkSUM:	Left (right) thigh Left (right) buttock Lower (upper) back pkTHL + pkTHR + pkBTL + pkBTR + pkLB + pkUB
Average peak contact pressure ratio	pkTHL/pkSUM, pkTHR/pkSUM, pkBTL/pkSUM, pkBTR/pkSUM, pkLB/pkSUM, pkUB/pkSUM	

To preserve the significance level for the 36 pressure variables as a whole, a multivariate analysis of variance (MANOVA) was conducted initially. Then, the same analysis methods (using different dependent variables) as in the companion paper (Kyung et al., in press) were used. Specifically, separate two-factor repeated-measures analysis of variance (ANOVA) for each of the 36 pressure variables to determine if there were main or interactive effects of Stature and Seat Condition, with the Tukey's honestly significantly different (HSD) test for post-hoc pairwise comparisons. Specific pairwise comparisons and contrasts were of interest as before: driving venue (lab vs. field) effects (S1-L vs. S1-F, U1-L vs. U1-F), seat effects within vehicle class (S1-L vs. S2-L, U1-L vs. U2-L), and linear contrasts of stature groups (middle vs. short + tall) and vehicle classes (S1-L + S2-L + S1-F vs. U1-L + U2-L + U1-F). These contrasts were selected, as it was anticipated in advance that anthropometric extremes would be less taken into account in seat design, compared to those of middle stature, and that there would be differences in preferences between vehicle classes. Among these post-hoc analyses, the comparison between sedan seats (S1-L vs. S2-L), and the contrast between vehicle classes (sedans vs. SUVs) were of particular interest, as only these two were found previously to be differentiated based on subjective ratings (Kyung et al., in press). Though not significant previously, driving venue effects were also of interest, as only one driving venue (field) involved exposure to road/vehicle vibration, which was expected to affect the pressure variables. Comparisons between bilateral body parts (thigh and buttock) were made using matched-pairs *t*-tests.

Additionally, bivariate coefficients of correlation (ρ) were obtained between each of the three subjective ratings and each of the 36 pressure variables. The presence of three statistical results were interpreted as supporting the general use of a pressure variable in seat design and evaluation, regardless of participant stature: (1) an association between a given pressure variable and any of the subjective ratings (comfort rating in particular, as it was the only subjective response able to distinguish among the Seat Conditions); (2) a significant Seat Condition effect (S1-L vs. S2-L in particular) on the variable; and (3) a lack of a significant Stature effect on the variable.

Relationships between dependent variables (i.e., subjective ratings and pressure variables) were further investigated using two steps: (1) a principal component analysis (PCA, based on the correlation matrix) to reduce the number of independent variables used in the subsequent regression analysis and (2) a multiple regression of each subjective rating on the factors from the PCA to determine if any subjective rating could be accounted for (based on model R^2) by a linear combination of the factors, which are in turn linear combinations of the pressure variables. The number of factors was determined by two criteria, the size of the eigenvalue (>1) and the cumulative percentage ($\approx 90\%$) of variance accounted for by the selected factors (Lehman et al., 2005). The selected factors were rotated by the varimax method. Finally, to determine the pressure levels that resulted in better comfort/discomfort ratings, two groups were defined: Group P (Perfect) that reported extremely strong comfort ($=10$) and no discomfort ($=0$) in their driving postures, and Group NP (Not Perfect) that had less than extremely strong comfort (<10) and some discomfort (<0). Group P included 24 cases from eight participants (three short, four middle and one tall), and Group NP 107 cases from 24 participants (eight short, seven middle, and nine tall). As there was only one tall participant in Group P, the Stature effect was not investigated. Five participants were included in both groups, whereas three were only in Group P, and 19 only in Group NP. The MANOVA and ANOVA models used for group comparisons were accordingly reduced to two factors (Group and Seat Condition). The remaining 29 cases, having an imperfect rating for either (but not both) whole body comfort or discomfort ratings, were excluded from this comparison. Statistical results were considered 'significant' or 'marginal' when $p \leqslant 0.05$ and $0.05 < p \leqslant 0.1$, respectively. One female participant did not complete the field sessions, but the lab data from this participant was included for analysis.

3. Results

3.1. Effects of Stature and Seat Condition on interface pressures

MANOVA showed that there were significant ($p \leqslant 0.0001$) main effects of Stature and Seat Condition on the 36 pressure variables as a group. From subsequent ANOVAs, three significant ($p \leqslant 0.032$) Stature × Seat Condition interaction effects were found, on avgTHL/avgSUM, avgBTR/avgSUM, and pkTHL/pkSUM (Note: no significant interaction effect was found in MANOVA). Significant ($p \leqslant 0.046$) Stature effects were found only on the three pressure variables that were related to average contact areas and ratio (aBTR, aUB, and aUB/aSUM). For all three variables, the same post-hoc groupings were obtained, B/AB/A for short/middle/tall. The tall group had larger contact areas at the right thigh and upper back, and larger contact area ratios at the upper back.

Significant ($p < 0.038$) Seat Condition effects were found on 31 pressure variables. Exceptions (pkLB, pkUB, pkTHR/pkSUM, pkBTR/pkSUM, pkUB/pkSUM) were all related to peak contact pressures or ratios. Significant mean differences between S1-L and S2-L were found for 13 pressure variables, and the same significant differences between these two seats were also found for comfort ratings (Kyung et al., in press), indicating that these two seats can be differentiated both objectively (using 13 pressure variables) and subjectively (using comfort ratings). Among these, four (i.e., aTHR/aSUM, avgLB, avgLB/avgSUM, and pkBTL/pkSUM) were higher in S1-L than in S2-L, whereas the other nine (aBTL, aBTR, aUB, avgTHL, avgTHR, avgTHL/avgSUM, avgTHR/avgSUM, pkTHL/pkSUM, and pkTHR/pkSUM) were lower in S1-L than in S2-L.

No stature group contrasts were significant ($p > 0.12$), whereas the contrast of vehicle classes (sedans vs. SUVs) was significant ($p \leqslant 0.048$) for 13 pressure variables. Among the latter, the means of nine variables were higher in the sedan class (aBTL, aLB/aSUM, avgTHR, avgBTL, avgBTR, avgUB, avgBTL/avgSUM, avgBTR/avgSUM, and pkBTL/pkSUM). The means of the remaining four variables (aTHL, avgTHL/avgSUM, pkTHL/pkSUM, and pkBTL/pkSUM) were lower in the sedan class. Among the pressure variables, 21 showed significant differences between lab and field settings in either of two vehicle classes (i.e., S1-L vs. S1-F or U1-L vs. U1-F). The differences between venues were substantial (Range: −56.1% to 87.5%, Table 3).

Significantly ($p < 0.0001$) larger contact areas and higher contact ratios were found at the right vs. left thigh (i.e.,

Table 3
Percent differences in mean contact area/pressure variables between lab and field settings by vehicle class (only significant differences are shown)

Variable group	Thigh		Buttock		Back	
	Left	Right	Left	Right	Lower	Upper
Area	−32.6[a]		−29.3 (−17.3)[b]	−33.6 (−21.9)	−56.1 (−38.5)	−21.3 (87.3)
Area ratio	(19.3)	16.7 (18.0)			−17.0 (−17.5)	
Pressure	(16.9)	(13.6)	18.3		11.8	8.8
Pressure ratio	−10.7 (10.4)	−9.5 (8.5)	10.2	(−17.2)		
Peak pressure	−14.5					
Peak pressure ratio	(14.1)	14.1	−15.4			

[a]Sedan (S1-L−S1-F)/S1-L∗100.
[b]SUV (U1-L–U1-F)/U1-L∗100.

Table 4
Coefficients of correlation (ρ) between subjective ratings and pressure variables (only significant correlations given)

Pressure variable	Overall rating	Whole body comfort rating	Three conditions[a] met?	Strict condition[b] met?
aTHL		−0.20	Y	
aTHL/aSUM		−0.20	Y	
aTHR/aSUM	0.16		Y	
avgTHL		−0.18	Y	Y
avgTHR		−0.25	Y	Y
avgBTL	−0.30	−0.20	Y	
avgBTR	−0.28	−0.21	Y	
avgUB		−0.19	Y	
avgBTL/avgSUM	−0.23		Y	
avgBTR/avgSUM	−0.22		Y	
avgLB/avgSUM	0.16	0.28	Y	Y
avgUB/avgSUM	0.18			
pkTHR	−0.18	−0.16		
pkBTL	−0.41	−0.24	Y	
pkBTR	−0.29	−0.17		
pkUB	−0.28	−0.25		
pkTHL/pkSUM	0.19		Y	
pkBTL/pkSUM	−0.19		Y	
pkBTR/pkSUM	−0.16			
pkLB/pkSUM		0.160		

[a]An association between a given pressure variable and any of the subjective ratings, a Seat Condition effect on the variable, and lack of a Stature effect.
[b]Three conditions above and association with comfort rating and distinction of the sedan seats (S1-L vs. S2-L).

2.3% more of the total contact area). In terms of average and peak contact pressure and ratio, the left buttock had significantly ($p \leqslant 0.0011$) higher levels than the right buttock (i.e., 2% more of the total average contact pressure and 3.4% more of the total average peak contact pressure).

3.2. Correlations between subjective ratings and pressure variables

There were 20 pressure variables significantly correlated either with overall or whole body comfort ratings ($-0.41 \leqslant \rho \leqslant 0.28$, Table 4). None, however, was significantly correlated with whole body discomfort ratings. Most (17) of the variables with significant correlations indicated pressures and ratios, and the remaining three were related to pressure areas. The largest correlation ($\rho = -0.41$) was found between pkBTL and overall ratings. Among the 20 variables, 14 variables (Table 4) met the three conditions noted earlier (i.e., an association with any of the subjective ratings, a Seat Condition effect, and a lack of a Stature effect). Three variables (Table 4) met stricter conditions of an association with comfort ratings and a distinction between sedan seats (S1-L vs. S2-L).

3.3. PCA and regression analysis using pressure variables

Nine factors with an eigenvalue >1 accounted for 87.8% of the total variance (Table 5). Based upon the smallest communality of 0.778 (found on pkUB/pkSUM), the variance of each pressure variable was well (at least 77.8% of it) accounted for by the selected factors. Each factor, based on review of the coefficients, appeared to have a more general interpretation (as indicated in

Table 5
Nine principal components after varimax rotation (underlined values are >0.6 and maximal across factors in their absolute values)

Pressure variable	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8	Factor 9
	Thigh vs. buttock (area)	Right buttock (pressure)	Left buttock (pressure)	Right thigh (pressure)	Buttock & lower back (area)	Lower back (pressure)	Left thigh (pressure)	Upper back (pressure)	Lower vs. upper back (area)
aTHL	0.822	−0.010	−0.126	0.147	0.164	−0.019	0.320	0.214	0.043
aTHR	0.823	−0.303	−0.084	0.241	0.067	−0.009	0.055	0.044	0.052
aBTL	−0.107	0.004	−0.059	−0.031	0.928	0.018	−0.089	−0.010	0.056
aBTR	−0.147	−0.056	−0.038	−0.112	0.915	0.040	0.072	0.017	0.080
aLB	0.198	−0.050	−0.161	0.033	0.799	0.169	0.007	−0.304	−0.329
aUB	0.322	0.100	0.040	0.219	0.388	0.043	0.178	−0.032	0.784
aTHL/aSUM	0.715	0.017	−0.097	0.074	−0.300	−0.087	0.270	0.342	−0.078
aTHR/aSUM	0.636	−0.348	−0.015	0.139	−0.493	−0.067	−0.086	0.151	−0.092
aBTL/aSUM	−0.778	0.082	0.057	−0.240	0.063	−0.075	−0.279	0.097	−0.261
aBTR/aSUM	−0.796	−0.004	0.075	−0.320	0.134	−0.048	−0.068	0.118	−0.208
aLB/aSUM	−0.126	−0.032	−0.155	−0.057	0.507	0.164	−0.108	−0.394	−0.632
aUB/aSUM	0.063	0.189	0.150	0.190	−0.106	−0.008	0.155	−0.016	0.914
avgTHL	0.322	0.222	0.010	0.518	0.001	0.123	0.634	0.059	0.208
avgTHR	0.421	0.192	0.070	0.808	−0.037	0.016	0.183	0.100	0.143
avgBTL	0.018	0.490	0.688	0.357	−0.144	0.142	0.116	0.066	0.248
avgBTR	−0.019	0.782	0.387	0.338	−0.006	0.131	0.075	0.103	0.211
avgLB	−0.094	0.063	0.143	0.237	−0.036	0.826	0.174	0.149	−0.031
avgUB	0.143	0.280	0.241	0.333	−0.120	0.205	0.025	0.692	0.224
avgTHL/avgSUM	0.281	−0.276	−0.447	0.104	0.079	−0.165	0.657	−0.109	0.045
avgTHR/avgSUM	0.491	−0.243	−0.335	0.621	0.020	−0.272	0.030	−0.010	−0.011
avgBTL/avgSUM	−0.188	0.242	0.819	−0.118	−0.149	−0.096	−0.141	−0.176	0.172
avgBTR/avgSUM	−0.213	0.832	0.212	−0.096	0.120	−0.092	−0.187	−0.086	0.119
avgLB/avgSUM	−0.245	−0.407	−0.210	−0.233	−0.002	0.650	−0.050	−0.015	−0.272
avgUB/avgSUM	−0.031	−0.383	−0.249	−0.320	−0.092	−0.152	−0.308	0.630	−0.072
pkTHL	0.281	0.095	0.099	0.263	−0.051	0.105	0.797	0.075	0.215
pkTHR	0.264	0.218	0.157	0.786	−0.113	0.030	0.205	0.140	0.178
pkBTL	−0.013	0.353	0.881	0.086	−0.069	0.053	0.015	0.098	0.098
pkBTR	−0.040	0.880	0.245	0.132	−0.089	0.054	0.075	0.074	0.089
pkLB	0.124	0.109	0.023	−0.076	0.129	0.852	−0.047	0.046	0.103
pkUB	0.167	0.265	0.210	0.276	−0.074	0.291	0.155	0.707	0.072
pkTHL/pkSUM	0.177	−0.383	−0.322	−0.001	−0.022	−0.198	0.739	−0.130	0.086
pkTHR/pkSUM	0.295	−0.158	−0.237	0.788	−0.072	−0.222	0.097	−0.012	0.133
pkBTL/pkSUM	−0.205	−0.087	0.824	−0.234	0.002	−0.279	−0.251	−0.122	−0.064
pkBTR/pkSUM	−0.189	0.881	−0.034	−0.092	−0.049	−0.186	−0.133	−0.134	−0.038
pkLB/pkSUM	0.019	−0.203	−0.266	−0.244	0.156	0.810	−0.180	−0.088	−0.029
pkUB/pkSUM	0.045	−0.260	−0.279	−0.036	−0.072	−0.046	−0.059	0.785	−0.054
Eigenvalue	9.120	7.547	3.853	3.198	1.919	1.782	1.751	1.260	1.172
Cum percent	25.33	46.30	57.00	65.88	71.21	76.16	81.03	84.53	87.79

Table 5). A subset of (3 to 4) pressure variables were found in each factor that predominantly determined the respective Factor level, as evidenced by large coefficients (>0.6). Further, these subsets of variables were mutually exclusive, and distinguishable in terms of relevant body part, or type of pressure, and factors were termed according to this (Table 5). For Factors 1 and 9 that were related to contact area ratios, coefficients with opposite signs were found between the thigh and buttock average contact area ratios (i.e., aTH(L or R)/aSUM vs. aBT(L or R)/aSUM), and between the lower and upper back contact area ratios (i.e., aLB/aSUM vs. aUB/aSUM), respectively. In other words, there were negative associations between the thigh and buttock and between the lower and upper back in terms of contact area ratio. For Factor 5, coefficients relating to contact areas of the bilateral buttocks and low back were all positive (hence, positive associations between the buttocks and low back in terms of contact area).

Regression analyses showed that overall and comfort ratings could be somewhat better accounted for ($R^2 = 0.24$ and 0.12, respectively) by the nine factors than could discomfort rating ($R^2 = 0.098$). Fitted models for overall and comfort ratings were significant ($p \leqslant 0.023$), while the model for discomfort ratings was marginal ($p = 0.071$). Based on the size of the standard beta weights, which represent the relative effects of each Factor on their dependent variable (Freund et al., 2003), increasing Factor 5 and decreasing Factor 3 would be effective at improving overall and whole body comfort ratings, as these had larger beta weights (Table 6). The largest and positive beta weights, for Factor 5 (13.7 and 8.5, respectively for overall and comfort ratings), indicated that increasing contact areas at the buttocks and lower back (specifically, aBTL, aBTR, and aLB) would be the most effective method for improving overall and whole body comfort ratings. Similarly, the second largest but negative beta weights, for Factor 3 (−10.7 and −6.8, respectively), suggest that decreasing average (peak) contact pressures and ratios relevant to the left buttock (specifically, avgBTL, avgBTL/avgSUM, pkBTL, pkBTL/pkSUM) would be the second most effective way of improving the two subjective ratings. Factor 4 had the third largest weights (10.1 and 7.2, respectively), suggesting a third strategy of increasing pressure levels and ratios at the right thigh.

Table 6
Regression coefficients and standard beta weights for regression models relating PCA factors to overall and whole body comfort ratings

Term	Overall rating		Whole body comfort rating	
	Estimate	Standard beta weight	Estimate	Standard beta weight
Intercept	82.35	0	6.77	0
Factor1	−0.12	−4.10	−0.01	−2.08
Factor2	0.91	5.74	0.13	4.35
Factor3	−2.06	−10.69	−0.25	−6.83
Factor4	1.36	10.14	0.18	7.24
Factor5	0.49	13.78	0.06	8.55
Factor6	−0.06	−0.46	−0.02	−0.77
Factor7	−0.88	−5.30	−0.10	−3.23
Factor8	−0.04	−0.53	−0.01	−0.98
Factor9	0.001	0.04	−0.006	−0.94

3.4. Comparisons between Groups P and NP

MANOVA showed that there were main effects of Group P/NP and Seat Condition on the 36 variables as a group ($p \leqslant 0.006$). ANOVAs showed that among the 36 variables, Group P/NP effects were significant ($p \leqslant 0.043$) for seven variables, whereas these effects were marginal ($p \leqslant 0.096$) for another four variables. Of interest was that Group P, versus NP, had lower pressure ratios at their left buttock, with 1.9% and 2.7% less of the total body pressure in terms of avgBTL/avgSUM ($p = 0.0008$) and pkBTL/pkSUM ($p = 0.027$), respectively (Fig. 2). Group P also had higher pressure ratios at their lower back with 1.3% more of the total body pressure in terms of avgLB/avgSUM ($p = 0.043$), and at their upper back with 1.2% more of the total body pressure in terms of pkUB/pkSUM ($p = 0.096$, Fig. 2).

Group P had balanced bilateral (peak) pressures and ratios at their buttocks ($0.21 < p < 0.79$ for avgBTL (/aSUM) vs. avgBTR(/aSUM) and pkBTL(/pkSUM) vs. pkBTR/(pkSUM)). In contrast, Group NP had higher pressures and ratios at their left buttock ($0 < p < 0.019$). For Group NP, an additional 2% of the total body pressure was found at their left buttock (0.22 vs. 0.20 for avgBTL/avgSUM, and 0.23 vs. 0.21 for pkBTL/pkSUM).

4. Discussion

This study focused on sitting comfort and discomfort during short-term driving, and used interface pressure data as objective measures with particular interest in the relationship between pressures and subjective responses. In the following, the specific driving duration used and the separation of comfort and discomfort are discussed. In addition, the experimental results are interpreted and recommendations are given for use of interface pressure in seat design and evaluation.

There is still debate on the proper experimental duration for studies related to human responses in seated postures. Shackel et al. (1969)'s study using office chairs showed that 5 min of sitting was sufficient to identify comfortable seats. Wachsler and Learner (1960) found no differences in sitting comfort ratings obtained during short-term (5 min) and longer-term (10, 15, 30 min, 4 h) trials. Reed et al. (1999) showed that 15 min was sufficient for posture 'settlement' in car seats, whereas Hanson et al. (2006) observed no difference in driving postures between 5 and 20 min of driving. In addition, judgments on long-term comfort were regarded as "very unstable and unreliable" (Branton, 1969). The present study used a 20 min duration (5-min

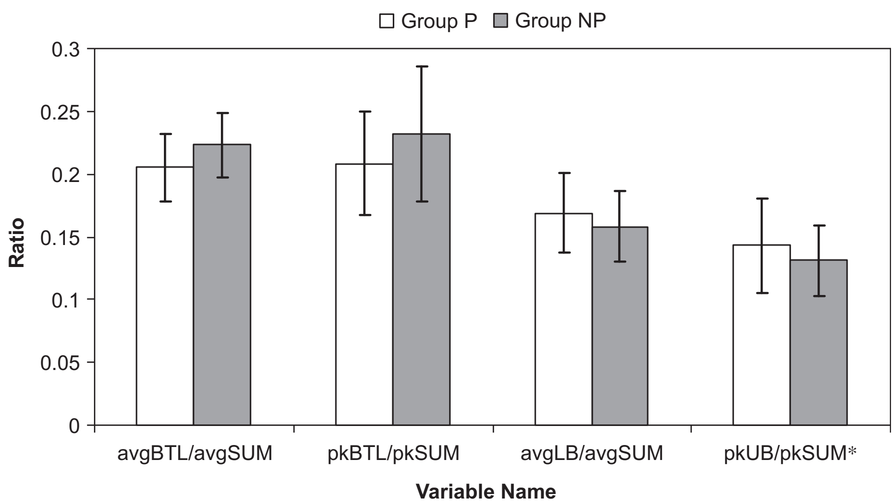

Fig. 2. Pressure ratios having significant Group (P vs. NP) effects (*: marginal effect, $p = 0.096$).

initial adjustments and 15-min driving), primarily to account for posture settlement.

Most mean pressure variables considered in this study showed a venue effect, or a difference between lab and field settings. Primary factors contributing to this discrepancy seem to be road/vehicle vibration, and more active operation of controls (pedals and steering wheel) involved in field studies. Therefore, lab studies without simulated vibration, though easier to conduct, may only be valid for measures of static comfort/discomfort, whereas on-road field studies, though done in a more realistic environment, will likely be limited to measures of dynamic comfort/discomfort. As a consequence, recommended pressure levels for sitting comfort/discomfort should be classified according to the underlying driving venue.

As opposed to the general consensus in the literature (i.e., that interface pressure is associated with discomfort), this study found that pressure data were more strongly associated with comfort. None of 36 pressure variables was significantly correlated with whole body discomfort, whereas 20 pressure variables were significantly correlated with either overall or whole body comfort ratings. This is also opposite to the expectation provided by de Looze et al. (2003), that objective physical measures such as interface pressure will be more directly associated with discomfort. In addition, only two regression models were significant, which related overall and whole body comfort ratings to composites of pressure variables. This offers an additional reason for the lack of a relationship between interface pressure and subjective ratings found by Gyi and Porter (1999), in that they only focused on discomfort and did not investigate comfort.

There is still no consensus as to what type of scale is best for relating comfort/discomfort to pressure. Shen and Parsons (1997) investigated the reliability and validity of six scales with respect to rating seated discomfort in the mid-thigh in response to four discrete levels of pressure stimuli (i.e., 60, 85, 120, and 165 mmHg). Among the six scales were the CP-50, the Borg CR-10 scale and Corlett discomfort scale. The other three were an 8-point ordinal scale, a modified intensity and discomfort scale, and a 21-point ratio scale. CP-50, a category partitioning scale, consisted of ‘no discomfort (0)’, five categories (1–50, 10 points for each) of ‘very slight’, ‘slight’, ‘medium’, ‘high’, and ‘very high discomfort’, and finally ‘maximal (>51)’. Reliability of each scale was determined by test–retest correlation, relative rating change, and coefficient of variation, whereas its validity was determined by “absoluteness of rating and functional consistency” (Shen and Parsons, 1997, p. 441). The authors concluded that the CP-50 was the best in terms of both reliability and validity.

While appropriate for the pressure range and body part involved, there are potential problems in directly using the CP-50 scale in a seat study involving both interface pressure and subjective ratings. First, an assumption used in the CP-50 scale descriptors (lower pressure = less discomfort) may not have internal/external validity if applied to other body parts. Results in the present study showed that for an individual to be more comfortable, the lower and upper back needed higher pressure levels than the experimental seats provided (higher levels of average lower/upper back contact pressure ratios were found in Group P), consistent with the work of Milivojevich et al. (2000). In addition, the validity of CP-50 is unknown when used at other, especially lower, pressure levels. Note that maximum pressure levels found here were 48.3 mmHg at the thigh and 69.1 mmHg at the lower back. Finally, it is also unknown whether the CP-50 can be used for comfort or overall ratings, with the same level of validity and reliability that were earlier demonstrated for discomfort.

The three stature groups in the present study had different values of average contact area in their upper back, and average contact pressure ratios in their lower and upper back. This stature effect indicates that different pressure requirements are needed for the seatback, as criteria in seat design and evaluation criteria. Previous studies have also shown the need for more adjustability in the seat back (Branton, 1984; Harrison et al., 2000; Kyung et al., in press).

From a PCA, contrasting associations were found between local body parts in terms of contact area ratio: negative associations between the thighs and buttocks, and between the lower and upper back, and positive associations between the buttocks and low back. These associations imply that, as might be expected, if some body parts (e.g., the buttocks and lower back) have large contact areas (hence, are supported more), then the other parts (e.g., the thighs and upper back) tend to have smaller contact areas (hence, are supported less). From these, two possible sitting strategies are apparent. One is described by sitting deep toward the seat biting line (where the seat cushion and back meet each other), corresponding to the case of having large contact areas for the buttocks and lower back. The other involves being slipped forward on the cushion and leaving a large space between the pelvis and the biting line, corresponding to the case of having large contact areas for the thighs and upper back.

People prefer to decrease the number of degrees of freedom in their seated postures to increase sitting stability (Dempster, 1955), and which can be attained by external and/or internal support (Hendriks et al., 2006). In driving, external support can come, for example, from the arm rest, steering wheel, head rest, foot rest, floor, and door and crash pad trims, or by getting sufficient contact area from these car parts. Internal support can be gained by supporting the head with the left or right hand or by putting a hand on the thigh. As less firm and inconsistent support is expected for the right foot (due to pedal operations), drivers can lean slightly to the left side to increase stability provided from the seat. If so, pressures at the left buttock should be higher than the right. Indeed, higher average and peak contact pressures and ratios were found at the left buttock in the bilateral comparisons using the pooled data, and more importantly this same result was found only in Group NP.

Asymmetric pressure distributions between the bilateral buttocks can be considered undesirable as they appear to lead to lower subjective ratings. As indicated earlier, Group NP (those reporting imperfect comfort and discomfort ratings) showed unbalanced bilateral pressure distributions at their buttocks (i.e., higher pressures and ratios on the left side). In contrast, Group P (reporting perfect levels of comfort and comfort) showed a balanced pressure distribution. Therefore, an alternative approach to the design of seat cushions may be needed. Asymmetrical seat design (in terms of contour) or use of different materials (in terms of hardness) between the bilateral seat buttock areas might facilitate more even pressure distribution and result in more comfortable seats. Evenly distributed pressure may also facilitate improved physiological responses (e.g., increase of blood flow and prevention of unnecessary muscular compensation and lactic acid accumulation), reduce feelings of discomfort, and delay fatigue (Cohen, 1998). The regression results in this study also suggest that lowering pressure and ratio levels in the left buttock will effectively increase (improve) overall and whole body comfort ratings. This was evidenced by the negative coefficient (and the large negative standard beta weight) of Factor 3 in the regression models, which was, in turn, predominantly and positively influenced by four pressure variables related to the left buttock area (i.e., avgBTL, avgBTL/avgSUM, pkBTL and pkBTL/pkSUM).

Beside bilaterally balanced pressure at the buttocks, a balanced distribution of pressure between lower and upper bodies was also found to relate to an improved sitting experience. Specifically, Group P had lower levels of left buttock pressure ratios, but higher levels of upper back pressure ratios than Group NP. This suggests that any additional pressure on the left buttock should be distributed to other body parts (especially to the upper back) to facilitate more balanced support of the whole body and ultimately to improve comfort/discomfort. This offers another partial explanation for Gyi and Porter (1999)'s results indicating no relationship between interface pressure and driving discomfort, as they only measured interface pressure on the right side of body.

Though the regressions of comfort (and overall) ratings on the pressure factors were significant, these models only accounted for a small portion of the total variability in subjective ratings. A shortcoming of these models, though, is that ratings for local body parts that were not in contact with the seat (e.g., neck, upper limbs, knees, and body parts below knees) were not effectively accounted for by using interface pressure. Other objective measures (e.g., joint angles), that incorporate these body parts, might explain a larger portion of the variability in responses. Alternatively, using both posture and interface pressure data is expected to account for more variability than using either alone.

Inherent here are the same potential limitations described in the companion paper (Kyung et al., in press). In brief, they are gender-confounded stature groups, aesthetic effects from other car parts except the seats, and participants' historical driving experiences. As these may have affected the subjective ratings (though probably not substantially), the relationships between pressure and subjective ratings reported here could have somewhat limited generality. Specific seats used in the experiments represent an additional limitation. The four experimental seats used, though carefully selected and representative of two different vehicle classes, could be distinguished from each other only in terms of comfort (Kyung et al., in press). Given this, it may have been unlikely to find a relationship between discomfort and pressure variables. However, it is also unlikely that a group of contemporary seats could actually be found that would be clearly distinguished in terms of discomfort (Helander, 2003; Shackel et al., 1969).

5. Conclusions

Several types of pressure variables were identified that were related with subjective responses and that distinguished between two groups with different levels of comfort/discomfort. Some pressure variables, derived in terms of average contact area and average (peak) contact pressure ratio, could be used across stature groups for the assessment of sitting comfort/discomfort. An improved sitting experience is argued as requiring a balancing of pressures between the bilateral buttocks as well as between the upper and lower body. Use of pressure data is suggested as more appropriate for assessing short-term comfort/discomfort, reflecting seat support and the distribution of body load on it, but not for the assessment of long-term discomfort (fatigue), due to inherent limitations in pressure measurement, and several potentially confounding influences. Larger-scale, more comprehensive experiments are required, firstly to determine preferred pressure values and ratios required for different vehicle classes, stature groups, and driving venues, and secondly to confirm the present findings that human–seat interface pressure is more strongly associated with comfort than with discomfort.

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MUSCLE LINES-OF-ACTION AFFECT PREDICTED FORCES IN OPTIMIZATION-BASED SPINE MUSCLE MODELING

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Abstract—This study describes the effects of varied torso muscle geometries commonly assumed in optimization-based muscle force prediction models. Specifically, the sensitivity of predicted muscle and spinal forces to assumed muscle lines-of-action (LOA) is systematically examined. The practical significance of varied muscle LOAs is addressed by determining the relative precision needed for individual muscle LOAs and assessing which muscles are more critical to accurate prediction of spinal forces. To perform this analysis a nonlinear optimization model was used to generate muscle force predictions during combined frontal and sagittal plane moment loadings with an assumed erect posture. The LOAs of the erector spinae, rectus abdominus, internal and external oblique, and latissimus dorsi were systematically varied in the frontal and sagittal planes over an anatomically feasible range. The results indicated that moderate changes in the assumed LOA could substantially alter the magnitudes of predicted muscle and spinal forces. The estimated activity level of a muscle, as well as the predicted active/silent state could be affected by the LOA of that muscle and others. The patterns of predicted muscle activity, with respect to load orientation, underwent only minor alterations with changing LOA. The relative activation of several muscles, however, was dependent on LOA, and frequently led to variations in predicted spinal compression (> 100 N change) and shear forces (> 50 N change). This dependence of estimated spinal forces on assumed muscle geometry was most pronounced for the obliques and minimal for the more vertically oriented muscles and when loads were sagittally symmetric. This study suggests that muscle LOAs are critical inputs when interpreting absolute muscle and spinal force values predicted by models of physical exertions.

INTRODUCTION

Various biomechanical models have been developed which allow the analysis of existing and proposed human exertions. The complex geometry of the structural components of the torso, though, makes such modeling a challenging activity. Of the many tissue components that can be included in a model, the muscles are of critical importance since they generate the majority of the restorative moments required to maintain equilibrium in most postures (McGill and Norman, 1986; Potvin *et al.*, 1991). Furthermore, these muscles act through moment arms that are relatively small, and the muscle forces required for even moderately strenuous activities can be large. This then imposes large forces on the spine. Hence, accurate estimation of spinal forces requires accurate determination or prediction of muscle forces.

Optimization-based predictive models attempt to mimic internal muscle recruitment strategies. They are predictive in the sense that if the external kinetic demands of a particular exertion are known or estimable, then the task can be analyzed without direct or invasive measurement. A predictive model of muscle activation, however, requires the definition of a scheme with which to resolve the muscle distribution problem. The number of muscle forces that can be generated within the torso exceeds the number of equilibrium equations, and the extra degrees of freedom imply a statically indeterminate system. Mathematical optimization methods have provided the primary means of overcoming the indeterminacy. By maximizing or minimizing an assumed objective, a unique set of muscle forces is obtained from the feasible set. Although a wide range of formulations has been developed, there is currently no apparent agreement regarding the best form of an optimization-based model (Hughes, 1991; Pedersen *et al.*, 1987; Pedotti *et al.*, 1978).

Regardless of the formulation, a muscle force model requires the specification of certain muscle geometric parameters, including each muscle's moment arm, cross-sectional area, and line-of-action (LOA). These geometric parameters are generally obtained from anatomic atlases (Moga *et al.*, 1992; Schultz *et al.*, 1987) or from cadaveric and radiographic studies (e.g. Chaffin *et al.*, 1990; Dumas *et al.*, 1991; Macintosh and Bogduk, 1991; Tracy *et al.*, 1989). The magnitude of predicted spinal compression and shear forces has been shown to depend heavily on assumed muscle moment arms (McGill and Norman, 1987), and implies that care must be used in determining these values. Predicted muscle forces, and to a lesser extent joint forces, can depend on estimated values of muscle cross-sectional area (Brand *et al.*, 1986). Strength curves, predicted using a geometric model, may vary depending on assumed muscle insertions and resting

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lengths (Kleweno and Winters, 1988). A detailed sensitivity analysis of assumed muscle lines-of-action, though, has not been previously studied.

The first objective of this study is to develop a method to determine whether muscle and spinal forces predicted with an optimization-based model will be altered greatly with muscle LOAs varied within an anatomically reasonable range. The second objective is to ascertain what practical significance is implied by any resulting sensitivities. Three questions will be addressed: (1) Which spinal forces are most dependent on muscle LOA, (2) Which muscles are most critical to the accurate prediction of specific spinal forces, and (3) How are predicted muscle force magnitudes affected by assumed LOA?

METHODS

The optimization-based muscle force prediction model used in this study originates from an objective function described by Crowninshield and Brand (1981) for the lower limb and implemented for the torso musculature by Hughes (1991). The objective $\Theta(\mathbf{f})$, is defined as the sum of the cubed power of muscle intensities (force/area). Its value is minimized in the model and thus will be referred to as the SCI (sum of cubed intensities) model. A unique set of muscle forces, **f**, is obtained by solving

$$\min \quad \Theta(\mathbf{f})=\sum_i (f_i/d_i)^3 \tag{1}$$

$$\text{s.t.} \quad \mathbf{Af}=\mathbf{b}, \tag{2}$$

$$f_i \geqslant L_i, \tag{3}$$

$$f_i \leqslant U_i, \tag{4}$$

where **A** is a matrix of moments resulting from unit muscle forces (incorporating both moment arm and LOA) and **b** is a vector of externally applied moments, hence (2) maintains moment equilibrium. Muscle forces are constrained to be above a minimum L_i, which is either zero or the force due to passive tissue strain when muscles are stretched beyond their resting lengths (in the present work only the upright posture is considered, hence all $L_i=0$). Muscle forces are also kept below a maximum U_i, computed as the product of a muscle's physiological cross-sectional area and the maximum muscle intensity (Ikai and Fukunaga, 1968). The SCI formulation serves to restrict muscle forces inversely proportional to their cross-sectional areas, d_i. Therefore, muscles with both large cross-sectional areas and moment arms which allow for resisting the applied moment will be preferentially recruited in the model. The muscles included in the model are the erector spinae (ES), latissimus dorsi (LD), external oblique (EO), internal oblique (IO), and rectus abdominus (RA).

Muscle moment arms correspond to averages obtained from a CT study of 19 male and female subjects (Moga *et al.*, 1993). Reference values for muscle orientations are averages from both the CT study and several anatomic studies in the literature (compiled in Moga *et al.*, 1992). Muscle cross-sectional areas were taken from Hughes (1991) who adapted values from Tracy *et al.* (1989). A single set of geometric values was used in this study, corresponding approximately to the anthropometry of a 50th percentile male in an upright posture (Table 1). Unit directional vectors are defined relative to a projected cutting plane that intersects the L3/L4 interspace. The LOA of a muscle is obtained by projecting the unit vectors in Table 1 onto either the sagittal or frontal planes, and is defined with respect to the global vertical axis. Conventions relating the LOA to anatomical directions are: $+x=$left, $+y=$dorsal, $+z=$cranial. Conventions for shear forces are: positive A–P and lateral shears correspond to L3 shearing anterior and right, respectively, versus L4.

Table 1. Normative muscle geometric data used in model: Muscle force components τ, triaxial moments resulting from unit muscle forces **m** (N cm), reference LOAs (deg.), and anatomical cross-sectional areas d (cm^2). Note that the unit directional vectors (τ) point caudally, which is the direction of muscle force. The Cartesian conventions for unit vectors are as follows: $+x=$left; $+y=$posterior; $+z=$cranial. The sagittal and frontal LOAs are w.r.t. the vertical: a positive sagittal value indicates the direction is anterior, a positive frontal angle indications the direction is medial. Values are shown for the erector spinae (LES, RES), rectus abdominus (LRA, RRA), internal oblique (LIO, RIO), external oblique (LEO, REO), and latissimus dorsi (LLD, RLD)

	τ			**m**			LOA		d
Muscle	X	Y	Z	X	Y	Z	Sagittal	Frontal	cm^2
LES	−0.076	−0.184	−0.980	−5.362	3.563	−0.253	10.6	4.4	24.9
RES	0.076	−0.184	−0.980	−5.362	−3.563	0.253	10.6	4.4	24.9
LRA	−0.101	0.083	−0.991	10.996	4.372	−0.752	−4.8	5.8	6.6
RRA	0.101	0.083	−0.991	10.996	−4.372	0.752	−4.8	5.8	6.6
LIO	0.534	0.570	−0.625	2.198	8.203	9.360	−42.4	−40.5	14.2
RIO	−0.534	0.570	−0.625	2.198	−8.203	−9.360	−42.4	−40.5	14.2
LEO	0.399	−0.360	−0.843	2.882	11.943	−3.741	23.1	−25.3	15.3
REO	−0.399	−0.360	−0.843	2.882	−11.943	3.741	23.1	−25.3	15.3
LLD	−0.138	0.081	−0.987	−4.861	10.235	1.520	−4.7	8.0	3.9
RLD	0.138	0.081	−0.987	−4.861	−10.235	−1.520	−4.7	8.0	3.9

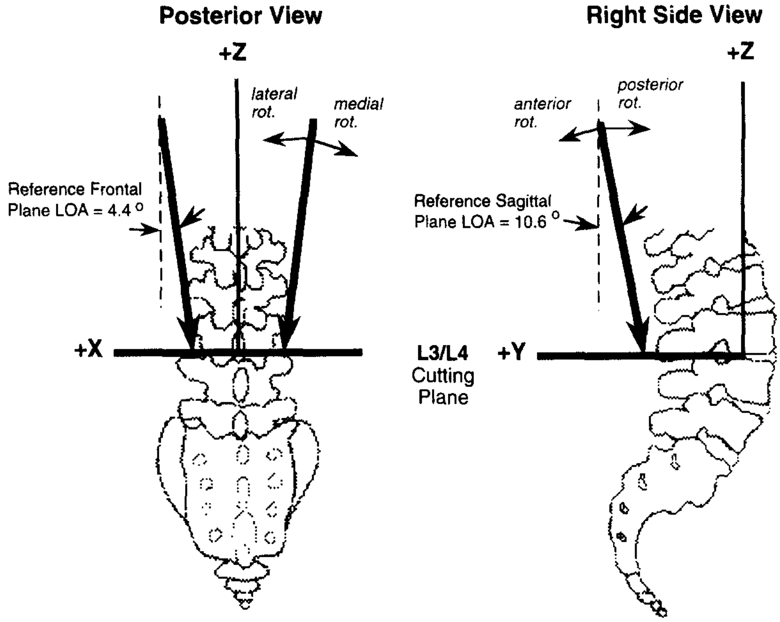

Fig. 1. Conventions for the coordinate system and rotations of muscle force vectors are illustrated for the erector spinae (some dimensions exaggerated for clarity). In the frontal plane, both muscles are rotated medially or laterally with respect to the vertical midline. In the sagittal plane, both muscles are rotated anteriorly or posteriorly with respect to vertical. The positive frontal and sagittal reference LOAs indicate that the ES force vector points medially and anteriorly, respectively. Rotations imply that the muscle force vector points more in the direction of rotation, e.g. medial rotation makes the vector point more medially.

The effects of changing muscle LOAs on predicted muscle and spinal forces were evaluated by systematically altering the LOAs of a *single set* of bilateral muscles (e.g. RES and LES) and observing how muscle and spine forces changed for a given external moment load. The LOAs (initial reference values given in Table 1) were varied in both the sagittal and frontal planes by rotating the unit vector for each bilateral muscle pair in a single plane (Fig. 1). The LOA above the cutting plane was rotated while keeping the location of the intersection of the LOA and the cutting plane fixed (the muscle moment arms were unchanged). In the sagittal plane the muscle pairs were rotated both anteriorly and posteriorly, and in the frontal plane rotated both medially and laterally.

The following rules were employed to maintain anatomic feasibility. Since it has been shown that the torso musculature is bilaterally symmetric with respect to moment arms (Chaffin *et al.*, 1990; Kumar, 1988), it was assumed that bilateral symmetry would also apply to muscle LOAs. Rotations were performed in both directions for each plane over a range of $\pm 20°$ in increments of 2°. An anatomically reasonable range, though differing for each muscle group, is probably narrower than $\pm 20°$ from the reference orientations. Results from Moga *et al.* (1992) demonstrated the extent of variability in lumbar muscle LOA obtained from both dissection and radiographic studies in the literature. These values are used for comparison, and indicated that feasible ranges of muscle LOAs in the frontal and sagittal planes are approximately: $\pm 5°$ for ES and RA; $\pm 10°$ for LD and IO; and $\pm 15°$ for EO. The cadaveric study of Dumas *et al.* (1991) revealed comparable ranges of muscle orientations with respect to a reference frame centered on L3/L4. Results and conclusions are presented only for these latter ranges.

The sequence of rotating the LOA and predicting the muscle and spinal forces was repeated using external moment loads applied in several orientations. The loads consisted of combinations of flexion/extension and lateral bending moments with a constant magnitude of 140 N m—approximately the maximum static flexion–extension moment reported for healthy subjects (Gomez *et al.*, 1991; Graves *et al.*, 1990; Parnianpour *et al.*, 1990). The external moments were applied in five directions: pure flexion (0°), flexion and right lateral bending (45°), pure right lateral bending (90°), extension and right lateral bending (135°), and pure extension (180°). Since the model is symmetric with respect to lateral bending moments, only those applied to the right are considered.

In order to summarize the effects on spinal forces observed with altered LOAs, arbitrary criterion levels for changes in spinal forces were defined; either >100 N change in compressive force or >50 N change in shear forces over the range of rotated LOAs. The 100 N spinal compressive force was chosen as indicative of the approximate accuracy desired in a biomechanical model for physical task evaluations, while a more conservative criterion was used for shear forces, since the relative risk of increasing shear forces has not been demonstrated conclusively. LOA effects on spinal forces, thereby, are classified as large, small, or not applicable because the muscle in question was not active or the spinal (shear) force was zero.

RESULTS

The process of determining spinal and muscle forces sensitivities to assumed muscle LOA is illustrated for the erector spinae (ES). Variation of the *frontal* plane LOA of the ES had only modest effects on the predicted spinal compressive and shear forces when the external moment load was applied to cause torso flexion. From a reference value of 4.4° (Fig. 1), the feasible range of orientations was from 9.4° medially to 0.6° laterally. The predicted compressive and shear forces over this range showed only minor changes of 3 N and 10 N, respectively. The lateral shear component was zero because of muscle symmetry with respect to the midline. The predicted ES force was minimized when the muscle was oriented vertically (0°) and rose approximately 20 N towards the extreme medial orientation. The ES behavior has a simple geometric interpretation. The ES is best suited for generating an extensor moment when it is oriented vertically, maximizing the z-component of its force vector (as noted above, we assume moment arms remain constant). Since the z-component is a cosine function of the LOA, only minimal changes occur near 0°, and the muscle force needs only to increase slightly to maintain a constant extensor moment. The compressive force remains unaffected because the majority (~95%) of the extensor moment is provided by the ES (the remainder from LD). Changes in shear force follow changes in ES force due to a small component of the ES force vector in the A–P direction. In the feasible range of orientations, all effects are considered small using the definitions given above.

With the load still applied in flexion, variation of the *sagittal* plane LOA of the ES also had relatively minor effects on the predicted forces. The ES was varied from a reference value of 10.6° and the new orientations ranged from 5.6 to 15.6° anteriorly. The change in compressive force over this range was minimal (4 N); however, the A–P shear and ES muscle forces varied to a greater extent than when the frontal plane angle was changed (300 and 30 N, respectively). The greater change in ES force occurs because the rotations create angles that are further from 0°, hence the z-component and subsequent extensor moment potential decreases more than with the frontal plane variations. Both the changing muscle force and its altered A–P component contribute to the changes in A–P shear, and over the feasible range of ES sagittal plane LOA, only the A–P shear effect is classified as large.

When the applied moment load was asymmetric, and the muscle undergoing variation was oriented obliquely, the effects of changing LOA were relatively greater for muscle and spine forces. A specific case is examined where the external load causes combined right lateral bending and extension of the trunk (load orientation = 135°) and the sagittal plane orientation of the EO is varied (Fig. 2). In this case, the muscle recruitment pattern is more complex than for an applied flexion moment in that the RA, EO, and IO are all recruited bilaterally. Over the feasible range of orientations, the compressive force has a moderate variation (177 N), and both the A–P and lateral components of shear change considerably (475 and 219 N, respectively), with the A–P shear displaying a switch in direction. Within the feasible region the

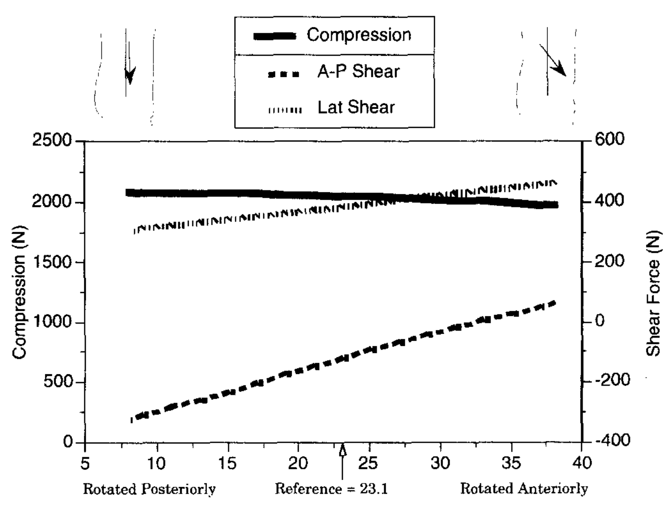

Fig. 2. Predicted L3/L4 compression and shear forces undergo large variation with changes in assumed EO geometry. The EO *sagittal* plane orientation is varied with an L3/L4 moment of 140 Nm applied at 135° (combined extension and right lateral bending). Over the range of ±15°, all three spinal forces undergo large variations. Note that the direction of the A–P shear changes at the extreme of anterior LOA rotation.

effects on the compressive, A–P shear, and lateral shear spinal forces are all classified as large. These changes are a result of a complex trade-off between recruitment of various muscles to resist the primary applied load and of secondary muscle forces needed to counterbalance moments created by the muscles themselves. The predicted RA forces are essentially unchanged, while the bilateral pairs of IO and EO undergo substantial changes (Fig. 3). The RIO decreases fourfold (400–100 N), the LIO almost doubles (352–588 N), and the LEO decreases slightly (780–689 N). Notably, the REO undergoes a transition at approximately 10°, where it is predicted to switch between active and silent states.

The previous examples are a small sample of the total simulations performed. Primary results are summarized using the above definitions of large, small, or not applicable, with the LOAs varied over the anatomically feasible ranges (Fig. 4). This summary provides an indication as to the dependence of spinal forces on the LOAs of specific muscles. Overall, the large effects were distributed equally between changes in sagittal and frontal plane LOA. Both A–P and lateral shear forces were observed to be affected by LOA changes in multiple muscles, especially when the load had some component of lateral bending. Large effects on compression were found only for loads applied in lateral bending and extension and resulted from changing only EO or IO orientations. Using the geometric interpretation given above, it is not surprising that when obliquely oriented muscles (EO and IO) were active in resisting the applied load, changes in their LOA often had large effects on spinal forces. An exception to this rule occurred for the IO sagittal LOA, which had only small effects for external loads at 45 and 90°. Further, changes in RA, when the load was applied to cause extension, had large effects on A–P shear. This occurred despite the nearly vertical orientation of the RA in both the frontal and sagittal planes, and reinforces the observation noted above (and shown in Fig. 3) that changes in the geometry of one muscle can markedly effect the predicted recruitment of other muscles. In the present case, the RA, EO, and IO are recruited bilaterally to resist the applied extension moment. As the LOA of the RA is altered away from the vertical, its force must increase if its moment contribution is to remain constant. Since the RA has a relatively small cross-sectional area, the growing intensity level is penalized (cubically) by the optimization objective function. The forces in the EO and IO, with larger areas but less mechanical advantage, increase and the spinal forces are thus altered.

The patterns of predicted muscle recruitment, considered over a range of external loads, underwent minor alterations with changes in muscle LOA. As an example, the EO muscle is considered while an external moment load of 140 N m is applied from various directions. The EO muscle is chosen for this evaluation because the changes in predicted forces with varying LOA were relatively large compared to ES, RA, IO, and LD. Changes in the frontal plane orientation of EO had small but consistent effects on the predicted recruitment pattern of that muscle. The LEO (Fig. 5A) shows a nonmonotonic response when three different EO frontal plane orientation angles are used. The qualitative behavior of the muscle changes

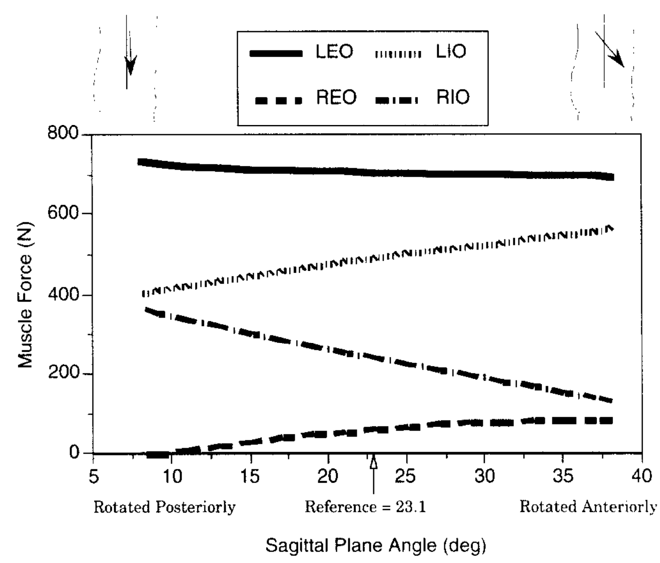

Fig. 3. Predicted EO and IO bilateral muscle forces are dependent on the assumed geometry of the EO. The *sagittal* plane orientation of EO is varied with an L3/L4 moment of 140 N m applied at 135° (combined extension and right lateral bending). The large changes in spinal forces (Fig. 2) result primarily from large changes in predicted muscle forces with changing EO orientation. Over the ±15° range, the IO forces change substantially, the EO forces somewhat less. Notably, the REO changes from silent to active at an EO sagittal plane orientation of approximately 10°.

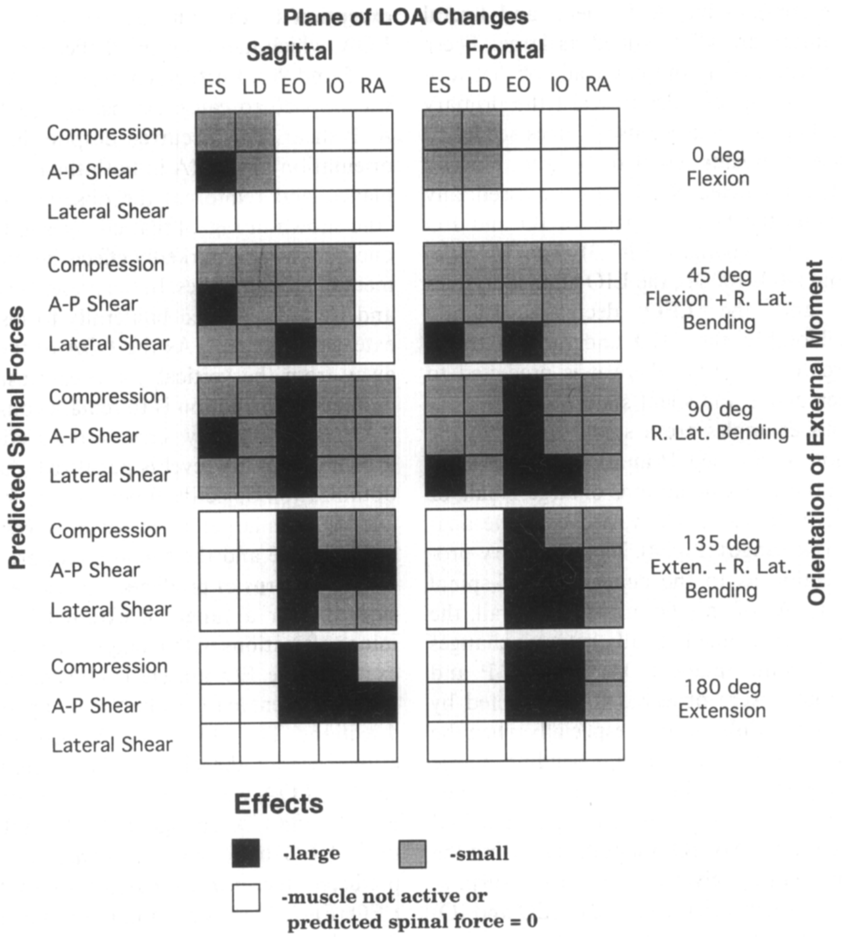

Fig. 4. Matrix illustrating effects on spinal forces when varying muscle LOA during application of a 140 Nm L3/L4 moment load. The two large columns correspond to the plane of rotation (sagittal or frontal) and the five large rows indicate the direction of the applied moment. Within each of the large rows, effects of changing muscle LOA are indicated for spinal compression and A–P and lateral shear. Using the definitions given in the Methods section, the effects are classified as large, small, or not applicable (because the muscle was not predicted to be active or the spinal force was 0). Large effects were seen for spinal forces primarily when the external moment load was in lateral bending or extension. Large effects on spinal compression resulted from changes in the oblique (EO and IO) muscles. Large effects on shear resulted from multiple muscles.

little with changing frontal plane orientation, but the magnitude of the first peak (near 120°) rises as the frontal plane orientation of EO is rotated inward. The REO (Fig. 5B) is predicted to be inactive over approximately the first 120° of external load orientation, after which the muscle response increases almost linearly. While the qualitative behavior of the muscle is consistent, the EO frontal plane orientation changes the load direction at which the REO is predicted to become active. Over the $\pm 15°$ through which the muscle orientation was varied, the load orientation at which the muscle turns on varied approximately 15°; outward rotation in the frontal plane caused the muscle to turn on for moment loads containing a smaller extension component relative to the lateral bending component.

Changing the EO frontal plane orientation also affected the predicted recruitment of other muscles (also seen in Fig. 3). As an example, substantial changes in IO activity were seen when considering the differential (left–right) forces. Regardless of the assumed EO frontal plane orientation, the differential IO forces (Fig. 6) peaked for loads consisting of lateral bending and extension (load orientation = 90–120°). Changing the frontal plane LOA of EO, though, caused large variations in the magnitude of the differential force. From a peak difference of approximately 300 N using the reference EO orientation, rotation of EO anteriorly increased the peak difference to 500 N, while posterior rotation caused the differential force to nearly disappear. The two previous examples are illustrative of a consistent finding. Changes in muscle LOA typically had moderate effects on the predicted recruitment pattern (Figs 5A and B), even though large variations in predicted forces were frequently seen for a single load (Fig. 3). More substantial effects

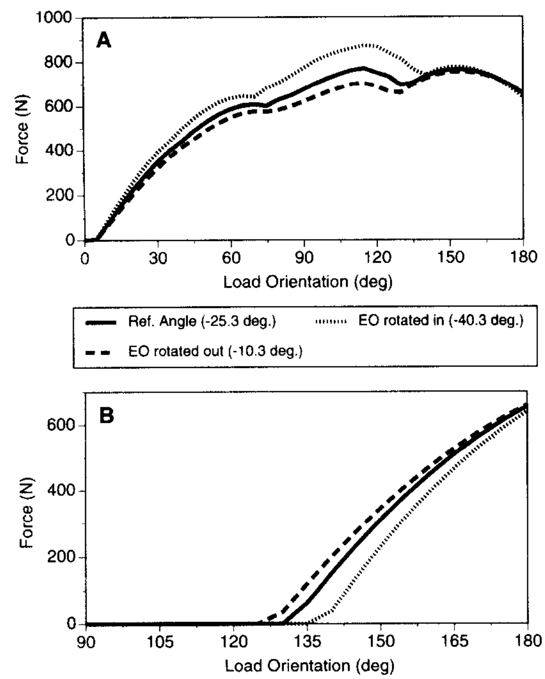

Fig. 5. Varying the EO *frontal* plane orientation moderately changes the predicted LEO (A) and REO (B) forces. With a 140 N m external moment load, the EO is rotated to the extremes of the anatomically feasible range, 15° in and out relative to the reference angle of −25.3°. The moment load orientation is varied from applied flexion (0)° through right lateral bending and extension (180°). The qualitative EO response patterns remains the same despite the changes in orientation. However, the relative magnitudes of the peaks in LEO response are altered as is the orientation at which the REO becomes active.

on recruitment patterns, though, were seen when considering multiple muscles (e.g. differential forces—Fig. 6).

A final note can be made regarding muscle recruitment patterns with changing load magnitude. Simulations were also performed using a smaller load moment, yet the model did not predict any qualitative changes in muscle recruitment patterns for the specific loading conditions studied. Muscles were either *active* for both magnitudes or *silent* for both magnitudes of loading. Thus, with smaller loads the effects of LOA variations on spinal forces were to change the magnitude of these effects only. The dependence of spinal forces on muscle LOA are the same as indicated in Fig. 4, although the magnitudes of the effects are proportional to the magnitude of the moment load.

DISCUSSION

In this study, the LOAs were varied over what was considered to be an anatomically valid range. Such a range was used since muscle LOA can differ with anatomical variations between individuals. Variations can as well result from differences in modeling technique, such as the use of fiber-line (Dumas *et al.*, 1991) or centroid-line (Jensen and Davy, 1975) representations. The simulations were performed using only a single set of anthropometric values and considered only the upright posture. It is reasonable to suppose that similar results will be obtained when varying anthropometry is incorporated. In nonupright postures, however, future work should consider the effects

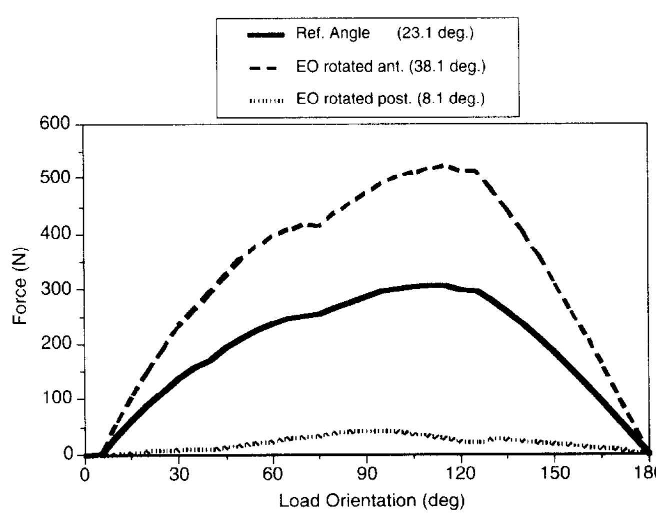

Fig. 6. Differential (left–right) IO predicted forces vary with the *sagittal* plane orientation of EO. With an applied 140 N m external moment load, the EO is rotated to the extremes of the anatomically feasible range, 15° in and out relative to the reference angle of −25.3°. The moment load orientation is varied from applied flexion (0°) through right lateral binding and extension (180°). At the reference LOA, the differential force peaks at approximately 120° of load orientation (combined right lateral bending and extension). The differential force increases or decreases (nearly to 0) when the EO sagittal LOA is rotated anteriorly and posteriorly, respectively.

of variation in muscle geometry induced by posture. Despite these limitations several important observations can be made concerning the dependence of force prediction models on muscle LOA.

Changes in muscle LOAs, of the order of 5–15°, were frequently found to have large effects on both A–P and lateral shear forces, using a criterion of a change >50 N. These effects were most prevalent when the load was asymmetric, involving some component of lateral loading. Variations in the LOA of all the muscle groups, except the LD, affected the magnitude of the predicted shear forces. Large changes in predicted spinal compression, using a criterion of a change >100 N, resulted only from muscles with oblique orientations (EO and IO). Given that there is a need for models that can accurately predict spinal forces, the results concerning the sensitivity of predictions have practical implications. For loads applied in pure flexion, only A–P shear was affected by LOA directional changes. McGill and Norman (1987) reported a similar finding in that shear rather than compression forces was affected by the variables used to describe the sacrospinalis at the L3/L4 level. Many biomechanical analyses involve pure flexion loads and this work suggests that the predicted compressive forces will be robust for a range of assumed muscle orientations. Although the moment arms of the active muscles (ES and LD) are still important, the use of a model during flexion-type loading need not be concerned with detailed investigation or representation of the LOAs: to a fair degree, any anatomically reasonable set of assumed LOAs will generate similar predictions. When the loading was asymmetric, multiple muscle groups were activated and many of these were found to substantially effect the predicted spinal forces. For analysis of asymmetric loading, the results suggest that the LOAs of most of the muscles must be accurately assessed (to within 5–15°) prior to inclusion in the model. Estimation of the orientation of the oblique muscles appears to be of greatest importance, especially given the large range in values presented for these muscles in the literature (Moga *et al.*, 1992).

Predicted spinal shear forces during asymmetric loading are highly dependent on the LOAs of several muscle groups. The magnitudes of the shear forces were seen to change nearly an order of magnitude with variations in muscle LOA, and in some situations the predicted shear forces changed direction. Obviously, the *in vivo* shear and compressive forces are not such variable quantities during controlled static loading. If models are to be used to estimate spinal shear forces, these results suggest that some caution must be used in interpreting the predicted values.

An important limitation of optimization-based models has been the difficulty in validating the accuracy of the predictions. Several studies have compared predicted forces with electromyographic (EMG) data. However, as Hatze (1980) and Hughes (1991) have shown, many formulations can generate force predictions that roughly agree with EMG patterns. Qualitative comparisons, such as active and inactive concurrence (Ladin *et al.*, 1989; Pedersen *et al.*, 1987), and quantitative comparisons of force and EMG (Huges, 1991) allow for elimination of obviously unsuitable models. Active and inactive concurrence, as a qualitative assessment, can be affected by LOA since, in some situations, the assumed LOA will result in altering the predicted active/inactive state of a muscle. More quantitative assessments have been done using linear regression of the predicted forces against the measured EMG of a particular muscle. The assumed LOAs, by affecting the pattern of predicted muscle recruitment, may change the derived force–EMG correlations. This does not refute the relative merits of comparing different objectives using consistent assumptions regarding muscle geometry. Instead, it suggests that assumptions regarding muscle LOAs, along with other details regarding muscle physiology and geometry, may be important limitations in the evaluation of model performance. The present model may also be limited by its simplicity. The complex torso musculature is reduced to five bilateral pairs, each of which is represented by only a single orientation. While deeper muscles (e.g. Psoas) may be active, their orientations tend to be vertical and their moment generating potential is limited by proximity to the lumbar motion segment (McGill *et al.*, 1988). Using a single orientation 'equivalent' to represent muscles is certainly a simplification, yet general conclusions obtained here should be applicable if muscles are represented more realistically with multiple orientations.

For a given model of muscle recruitment, inaccurate predictions may be made either because the model is a poor abstraction of reality or it may have the proper structure with poor parameter values. Implicit in the present work is the assumption that the latter source of error predominates. We have assumed that the SCI model is a reasonable simulation of human motor control based on previous empirical evaluations comparing predicted forces with EMG (Hughes, 1991; Nussbaum *et al.*, 1991). In addition, though not presented here, we have performed similar sensitivity analyses using a linear optimization model (Schultz *et al.*, 1987; Bean *et al.*, 1988). Similar conclusions were obtained, in that large effects on spinal compression were caused only by variation of the LOA of muscles whose initial orientation was more oblique, and large effects on spinal shear usually occurred when the applied moment was asymmetric. Thus, the determination that muscle LOAs affect predicted forces appears independent of the specific choice of optimization formulation and likely pertains to a wide class of such predictive models.

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The influence of age on isometric endurance and fatigue is muscle dependent: a study of shoulder abduction and torso extension

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The present study examined differences in isometric muscle capacity between older (55–65 years) and younger (18–25 years) individuals. A total of 24 younger and 24 older participants (gender balanced within each group) performed sustained shoulder abductions and torso extensions to exhaustion at 30%, 50% and 70% of individual maximal voluntary contraction (MVC). Along with endurance time, manifestations of localized fatigue were determined based on changes in surface electromyographic signals obtained from the shoulder (middle deltoid) and the torso (multifidus and longissimus thoracis) muscles. Strength recovery was monitored using post-fatigue MVCs over a 15-min period. Compared to the younger group, older individuals exhibited lower muscular strength, longer endurance time and slower development of local fatigue. Age effects on fatigue were typically moderated by effort level, while effects of gender appeared to be marginal. Non-linear relationships between target joint torque and endurance time were observed, with effects of age differing between shoulder abduction and torso extension. Overall, the effects of age on endurance and fatigue were more substantial and more consistent for the shoulder muscle than for the torso muscles and were likely related to differences in muscle fibre type composition. For strength recovery rates, no significant age or gender effects were found in either experiment. In summary, this study suggests that differences in isometric work capacity do exist between older and younger individuals, but that this effect is influenced by effort level and the muscle tested.

Keywords: Aging; Isometric exercise; Muscle fatigue; Muscle endurance; Strength recovery

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1. Introduction

Census Bureau population projections suggest that there will be around 75 million people over the age of 55 years in the United States in 2010, resulting in an increase of about 46% in the number of older workers between the ages of 55 to 64 years compared to the year 2000 (Horrigan 2004). The increasing percentage of older workers in the workplace necessitates re-evaluation of their physical work capacity. A decline in physical capability may exist in general among older workers, but limited data are available.

Aging has well-known associations with sarcopenia (loss of skeletal muscle mass). Although age-related decreases in physical activity may contribute to this loss, several underlying changes in the neuromusculoskeletal system have been identified as primary contributors to sarcopenia, including a reduction in the number of active motor units, a slower firing rate of motor units, a smaller number of muscle fibres and smaller fibre size (Campbell *et al.* 1973, Lexell *et al.* 1988, Evans 1995). As a result, age-related declines in muscular strength have generally been reported, but these losses appear to vary among different muscle groups (Bemben *et al.* 1991, Bäckman *et al.* 1995).

Along with sarcopenia, a shift in the relative proportions of muscle fibre types occurs with advancing age due to a selective reduction in type II (fast-twitch) fibres (Lexell 1995, Klein *et al.* 2003). The shift in fibre type proportion has been hypothesized to play at least a partial role in the longer endurance times reported for older individuals in sustained knee extension and elbow flexion (Larsson and Karlsson 1978, Bilodeau *et al.* 2001b). In addition to endurance, aging also results in a higher fatigue resistance, based on changes in electromyographic (EMG) measures. At the same levels of prolonged submaximal efforts, older individuals have demonstrated lower rates of EMG amplitude changes during exercises involving the elbow flexors (Bilodeau *et al.* 2001b) and slower rates of decline in EMG spectral measures recorded from the ankle dorsiflexors (Merletti *et al.* 1992, Yamada *et al.* 2000). Further study is necessary to investigate whether age effects consistently exist across muscle groups, specifically for muscles frequently used in occupational settings.

In addition to muscle strength and fatigue, physical work capacity is influenced by post-exertion recovery (e.g. in intermittent or cyclic work). However, the relationship between aging and recovery from exercise-induced local fatigue has received relatively little attention (Allman and Rice 2001). Several measures (e.g. measurements of voluntary strength, EMG changes, twitch response) have been used to monitor recovery, but evidence is often contradictory. For example, older subjects were found to have slower recovery of muscle fibre conduction velocity and EMG median frequency (Hara *et al.* 1998), yet no significant age effects on recovery of voluntary strength and EMG parameters were reported (Allman and Rice 2001, Bilodeau *et al.* 2001a).

The purpose of the present study was to quantify differences in muscular endurance, fatigue and recovery between older and younger individuals in response to several levels of sustained isometric effort. Existing evidence has clearly identified several changes in the neuromuscular system and demonstrated some consistent age effects on muscular performance and recovery. However, most of this evidence has been obtained from a limited set of muscles (Allman and Rice 2002). In this study, two muscle functions were investigated; specifically, shoulder abduction (middle deltoid) and torso extension (lumbar extensors). These were selected for three main reasons. Occupationally, symptoms and complaints related to the shoulder (Van der Windt *et al.* 2000) and torso

(Guo *et al.* 1999) are common among industrial workers. These muscles differ in fibre composition. While the proportion of slow-twitch fibres of the middle deltoid is about 53–69% (Manta *et al.* 1996), the lumbar extensors (e.g. the longissimus muscle) have approximately 71% slow-twitch fibres (Jørgensen 1997). Furthermore, shoulder and torso muscles can be considered functionally different (task vs. postural muscles, respectively). The last two reasons are related to each other. The functional distinction between the muscles is due to differences in fibre type composition and the lumbar extensors were considered as postural muscles due to the high proportion of slow-twitch fibres. It was therefore hypothesized that age-related differences in muscular capacity would differ between the two muscle groups. Given the projected increase in the older worker population in the workplace, the study was focused on older individuals whose age was typical of that at the end of working life. As has been done in several recent studies, effort levels used here were normalized to individual capacity in order to isolate endurance/fatigue from confounding effects of age-related strength decrements.

2. Methods

Fatigue development and recovery were evaluated under different workload conditions using a repeated measures design. To address variations in motor unit control with exertion level (De Luca *et al.* 1996), three levels of sustained isometric activity were used (30, 50 and 70% of maximum voluntary contraction (MVC)). Two separate experiments were conducted, one addressing shoulder abduction and the other torso extension.

2.1. *Participants*

For each experiment, a total of 24 younger and 24 older individuals were recruited from the local community, with gender balanced within each group (table 1). Only those with moderate levels of (self reported) daily physical activities and having had no injuries or disorders in the past 12 months were included. All older participants were screened for any contraindications to performance in experimental procedures based on examination of an occupational physician. The younger participants typically held non-sedentary jobs. The older individuals, although not all held a full time job, performed regular moderate exercise. Informed consent, using procedures approved by the Virginia Tech Institutional Review Board, was obtained prior to the experiment.

2.2. *Procedures*

Each experiment required three sessions, performed on 3 separate days, with a minimum of 2 d of rest in between. Each session consisted of pre-fatigue MVCs,

Table 1. Descriptive data on participants. Values are mean $\pm$ standard deviations.

	Experiment 1 Shoulder abduction		Experiment 2 Torso extension	
	Younger	Older	Younger	Older
Age (years)	21.7 $\pm$ 1.9	61.5 $\pm$ 4.3	21.5 $\pm$ 1.2	60.8 $\pm$ 4.0
Stature (cm)	170.8 $\pm$ 7.7	167.3 $\pm$ 7.8	172.8 $\pm$ 9.0	166.9 $\pm$ 7.7
Mass (kg)	71.5 $\pm$ 13.6	78.5 $\pm$ 14.0	71.6 $\pm$ 10.9	77.0 $\pm$ 14.1

endurance testing (at an effort level of 30, 50 or 70% MVC) and post-fatigue (recovery) MVCs. To minimize potential order effects, effort levels were performed in a counterbalanced order for each age and gender group. Detailed procedures for each experiment are described below.

2.2.1. Experiment 1: Shoulder abductions. Each participant was comfortably stabilized with shoulder and waist straps in a seated position in a dynamometer (Biodex™ System 3 Pro Medical System, Biodex Medical Systems, Shirley, NY, USA). The dynamometer's centre of rotation was aligned with the centre of the shoulder joint, approximated below the acromial process according to Nussbaum and Zhang (2000). After a brief warm up, each participant was instructed to perform MVCs by maximally abducting their right arm in the frontal plane against the dynamometer padding while the arm was horizontal (figure 1a). The left arm remained resting at the participant's side. Each recorded MVC value was corrected for gravitational effects on the participant's arm and dynamometer attachment. A minimum of three MVCs were performed, with 2 min of rest given between. Additional MVCs were performed if the torque exerted markedly increased (more than 10%) from the previous trial. The largest torque was designated as the participant's MVC.

Following a 10 min rest, each participant performed an isometric endurance test at one of the three effort levels, with procedures as follows. All postures were the same as those used during the MVC tests. After brief practice, each participant was instructed to maintain the exertion level within $\pm 5\%$ of the target torque for as long as possible. Torque feedback was displayed on a computer screen located directly in front of the participant. Following cessation of the isometric endurance test, a series of MVCs was then performed (post-fatigue MVC) during recovery at 0, 1, 2, 5, 10 and 15 min. A similar sequence of pre-fatigue MVCs, endurance test and post-fatigue MVCs was repeated on subsequent days at the remaining effort levels. Non-threatening verbal encouragement was provided throughout each test and efforts were made to ensure that participants were comfortable. All postures and fixture configurations were recorded and kept consistent across experimental days.

2.2.2. Experiment 2: Torso extensions. Torso extension tasks were performed using procedures similar to those in the shoulder exertions (pre-fatigue MVCs, endurance test and post-fatigue MVCs). Each participant was stabilized using a hip fixture designed to maintain an upright posture with hips and knees strapped to padded constraints (figure 1b). A force plate (OR6; Advanced Mechanical Technology Inc., Watertown, MA, USA) was placed underneath the fixture and torques exerted (at the L5/S1 level) were estimated from the recorded force and relative distance to the force plate (Granata *et al.* 1996). During MVCs, participants were instructed to stand upright and to maximally extend the torso in the sagittal plane against padding placed over the upper torso (as shown in figure 1b). A strap over the upper torso was used to maintain an upright posture. All other test procedures were the same as those employed during shoulder abductions.

2.3. *Surface electromyographic signal acquisition and processing*

Surface EMG signals were obtained from the middle deltoid during shoulder abductions, using a pair of Ag/AgCl electrodes (inter-electrode distance of 2.5 cm) located over the muscle belly (Hermens *et al.* 1999). During torso extensions, four pairs of the electrodes

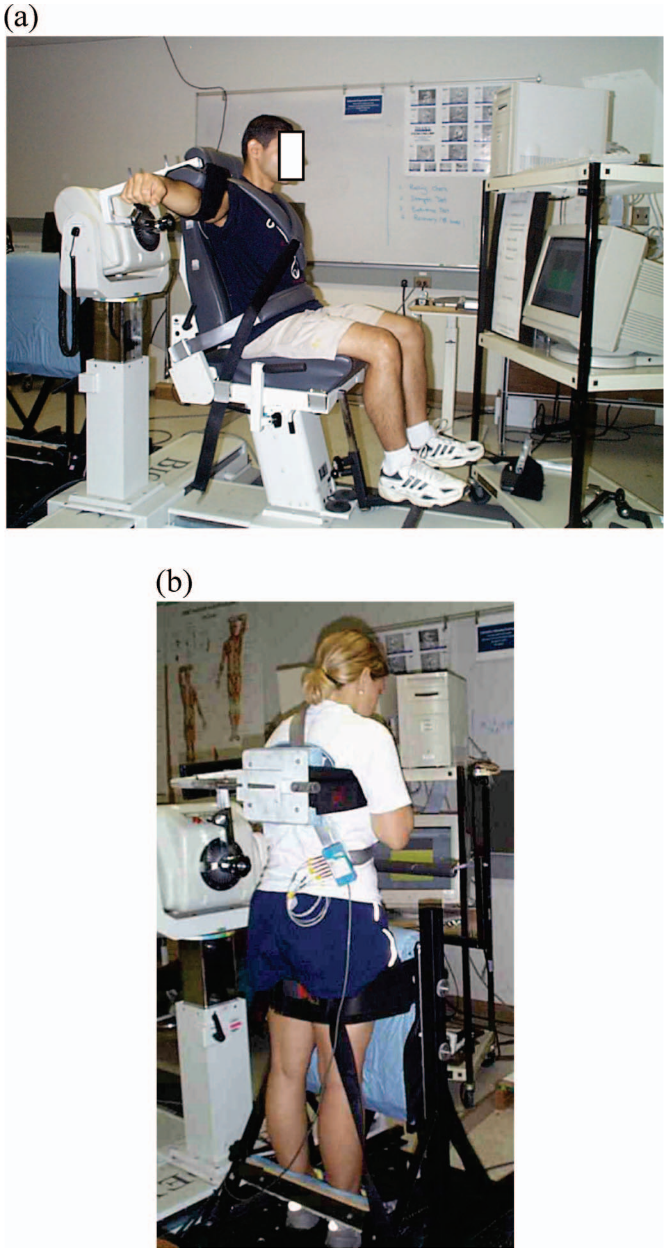


Figure 1. Experimental arrangement for (a) shoulder abduction and (b) torso extension.

were placed bilaterally over the erector spinae muscles at the L1 and L4/L5 levels, to target the longissimus thoracis and the multifidus muscles, respectively, according to Biedermann *et al.* (1990) and Larivière *et al.* (2002). Electrode locations were marked and recorded to ensure consistent placement in subsequent experimental sessions. Prior to electrode placement, the skin was shaved, gently abraded and cleaned with rubbing alcohol, with an inter-electrode resistance less than 10 kΩ considered acceptable. The clavicle or the C7 vertebral process was used for grounding.

EMG signals were recorded continuously during both experiments using an EMG amplifier system (Measurement System Inc., Ann Arbor, MI, USA). Raw signals were pre-amplified ($\times 100$) near the electrode site and hardware filtered at 10–500 Hz. Raw EMG was sampled at 2048 Hz, while EMG root mean square (RMS) was sampled at 128 Hz (110 ms time constant). The former were then divided into 2 s samples and subsequently divided into three 1 s overlapping windows (Luttmann *et al.* 1996). A Hanning window and Fast Fourier transform were applied to each sample window. A final power spectral density was calculated as an average value and used to determine the mean and median frequencies (MnPF and MdPF, respectively) according to Merletti and Lo Conte (1995). EMG RMS was low-pass filtered using software (Butterworth, zero phase-lag, 4th order, 3 Hz cutoff). Each 1-s sample of EMG RMS taken during endurance tests was averaged and normalized (nRMS) against maximum RMS values obtained during initial MVCs.

2.4. *Analysis*

Independent variables included age group, gender and level of submaximal effort, while dependent measures were endurance time, rates of EMG changes (nRMS, MnPF and MdPF), rate of MVC decline and rate of strength recovery. Endurance time was defined as the time during which torque was maintained in the target zone ($\pm 5\%$). Linear regressions were applied to time-dependent changes in EMG measures (RMS, MnPF and MdPF). The slopes obtained were then normalized to intercept values to obtain rates of EMG change in %/min. Rates of MVC decline (%/min) were computed as the percentage reduction in MVC (pre- vs. post-fatigue MVC) relative to individual endurance time. Strength recovery (post-fatigue MVC) was also represented as a percentage of pre-fatigue MVC.

A three-way repeated measures ANOVA was generally used to examine the presence of main and interaction effects of age, gender and effort level. Since individual strength (MVC) may be a factor influencing fatigue development, an initial test was conducted to investigate the effect of this potential covariate. If the covariate (MVC) was significant and a common slope parameter existed, a three-factor repeated measures analysis of covariance (ANCOVA) was chosen. Results showed that the prerequisite ANCOVA conditions were not found for any dependent measures during the shoulder experiment, but were observed for all EMG-based fatigue parameters for the torso. Thus, for the latter measures, ANCOVA was employed following Winer *et al.* (1991). Where relevant, post-hoc analyses were conducted using Tukey's HSD test. To examine the relationship between endurance time and target torque magnitude, logarithmic transformations were applied for the latter data and then regression analysis was performed to determine the existence of age and gender effects on the relationship.

To analyse strength recovery, post-fatigue MVCs were fitted to exponential models, $Y = A * (1 - \exp^{-\lambda t})$, as suggested by Elfving *et al.* (2002), where λ represents the rate of recovery (per min). Subsequently, any effects of the independent variables on λ were determined using a three-way repeated measures ANOVA. Repeatability of pre-fatigue MVC across days was also of interest (since different MVCs were obtained on different days) and this was assessed using intra-class correlations (ICC), SEM and coefficients of variation (CV) following Denegar and Ball (1993) and Elfving *et al.* (1999). Significance for statistical tests was concluded at $p < 0.05$, unless otherwise specified.

3. Results

There were effects of effort level for all measures, with some evidence of age and age × effort level interaction effects for most of the measures. More detailed results for each dependent measure are described in table 2 and below.

3.1. *Initial maximum voluntary contraction*

Age and gender significantly affected isometric strength in both experiments (figure 2). Mean shoulder abduction MVCs were 64.5 and 52.4 Nm, respectively, for younger and older participants (a difference of approximately 19%). An interactive age × gender effect was also significant, with a greater age-related difference among males than females. For torso extension, a larger MVC discrepancy between the two age groups (about 27%) was found, with an age × gender interaction trend observed ($p = 0.12$). For both experiments, MVC across days was found to be highly repeatable (ICC > 0.96) with fairly small variability (SEM 2.4 Nm for shoulder abduction and 10.5 Nm for torso extension; CV < 4.9% for both).

3.2. *Endurance time*

Shorter endurance times were associated with increased effort level (figure 3). The effect of age on endurance time was significant for the shoulder (with a difference of 13.2% across effort levels), but not significant for torso extension. Gender was not significant for shoulder endurance, but a trend was observed during torso extensions ($p = 0.11$), with females having 11% longer endurance across effort levels. A trend indicating an age × effort level interaction was obtained for the shoulder ($p = 0.13$), suggesting a greater age-related discrepancy at lower effort levels.

Table 2. Summary of main and two-factor interactive effects for each dependent measure, during shoulder abduction (SA) and torso extension (TE).

		Main effects			Interactions		
Measure	Task	A	G	EL	A × G	A × EL	G × EL
Endurance	SA	*	NS	***	NS	NS	NS
	TE	NS	NS	***	NS	NS	NS
EMG RMS	SA	NS	NS	***	NS	NS	NS
	TE†	NS/NS	NS/NS	***/***	NS/NS	NS/NS	NS/NS
EMG MnPF	SA	***	NS	***	NS	*	NS
	TE†	*/**	NS/NS	***/***	NS/*	***/***	NS/NS
EMG MdPF	SA	***	NS	***	NS	*	NS
	TE†	NS/**	NS/NS	***/***	*/*	***/***	NS/NS
Rate of MVC decline	SA	*	NS	***	*	NS	NS
	TE	NS	NS	***	NS	NS	NS
Recovery rate	SA	NS	NS	NS	NS	NS	NS
	TE	NS	NS	NS	NS	NS	NS

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

†Values for the longissimus thoracis and multifidus muscles, respectively.

A = age; G = gender; EL = effort level; EMG = electromyographic; RMS = root mean square; MnPF = mean power frequency; MdPF = median power frequency; MVC = maximum voluntary contraction.

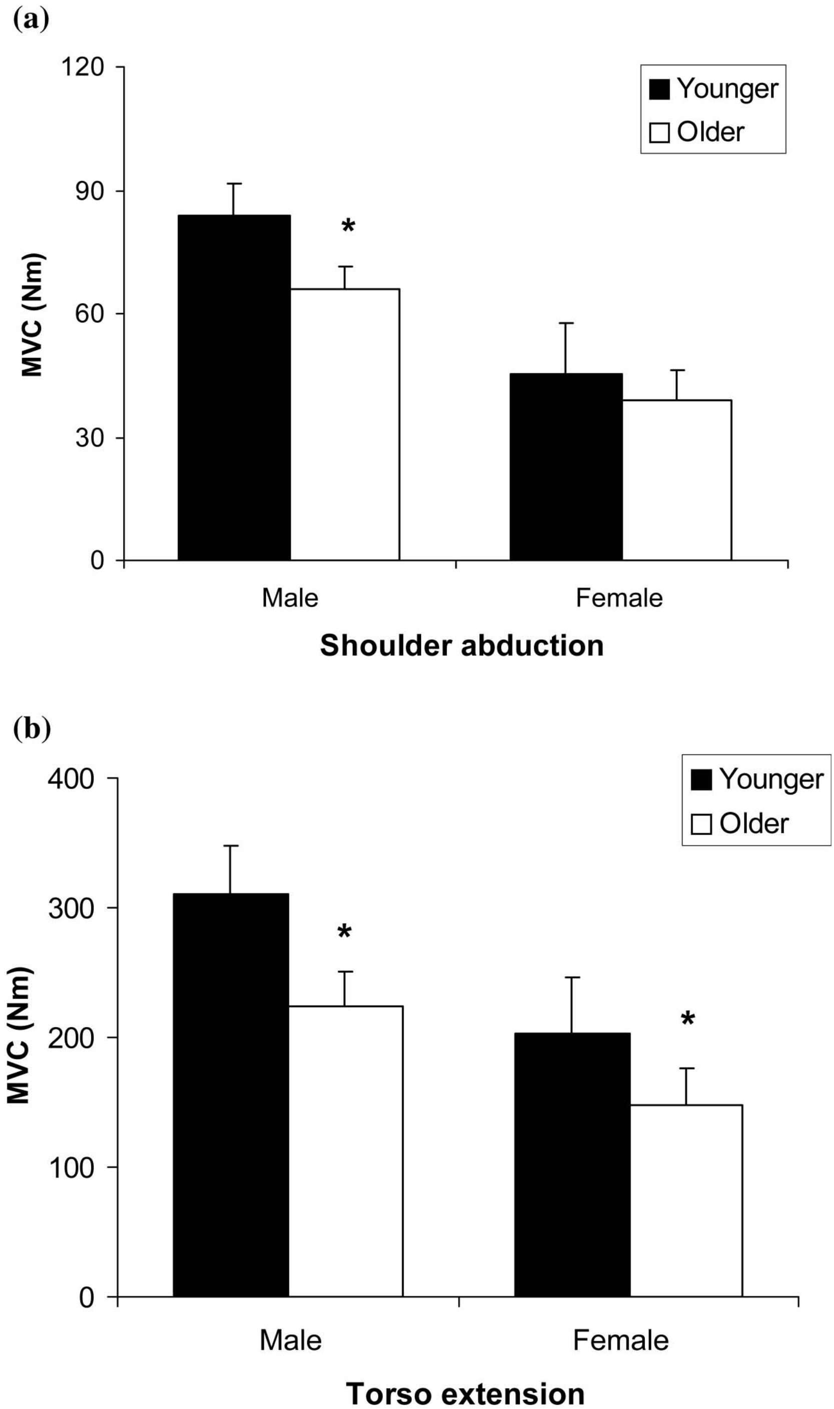
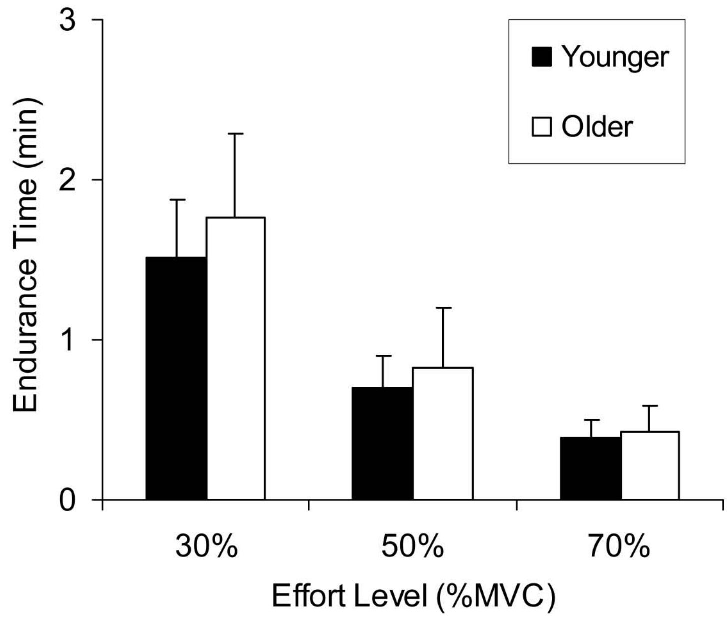


Figure 2. Maximum voluntary contraction (MVC) values for (a) shoulder abduction and (b) torso extension. Error bars represent standard deviations and * indicates significant differences.

(a)



(b)

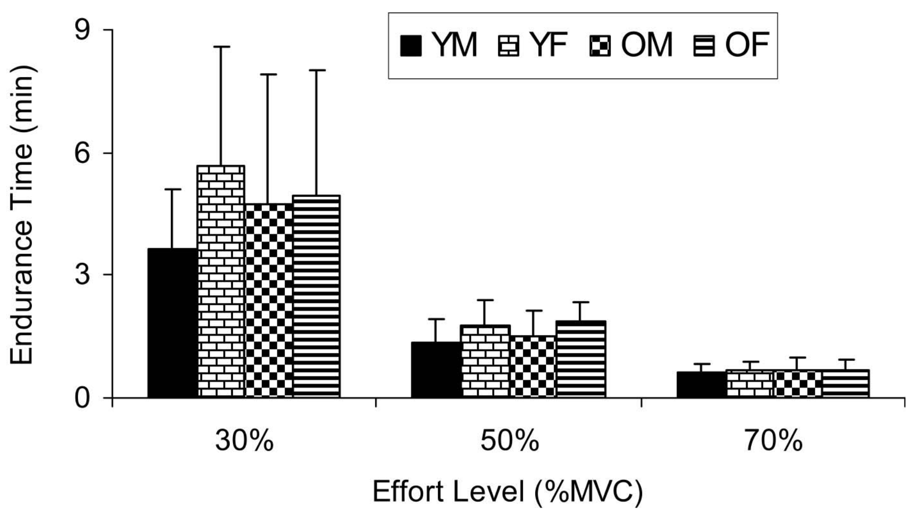
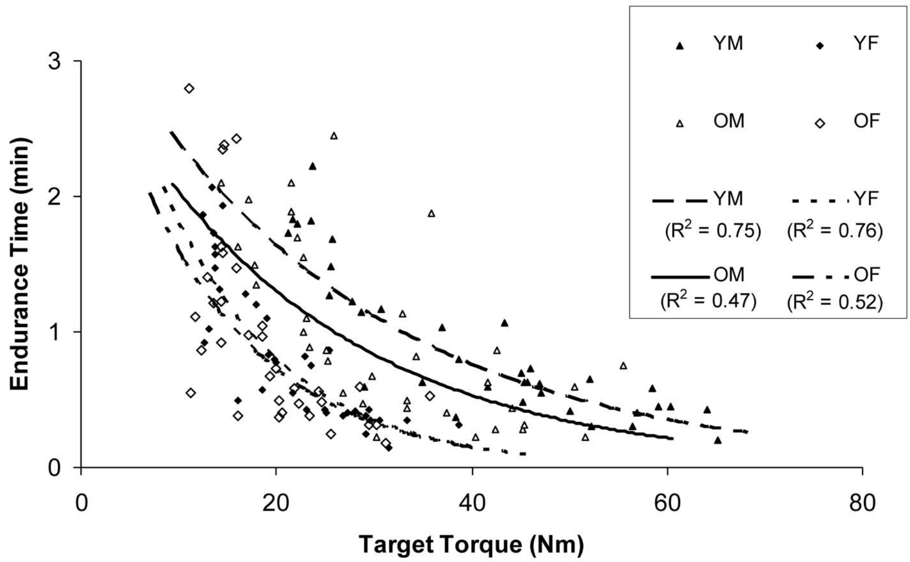


Figure 3. Endurance times for (a) shoulder abduction and (b) torso extension. Error bars represent standard deviations. YM = younger male; YF = younger female; OM = older male; OF = older female; MVC = maximum voluntary contraction.

Endurance time demonstrated an inverse relationship with target torque magnitude (figure 4) and was well-characterized using a negative exponential function ($r^2 = 0.46 - 0.76$). Gender effects were significant for both experiments. For the shoulder, an age effect

(a)



(b)

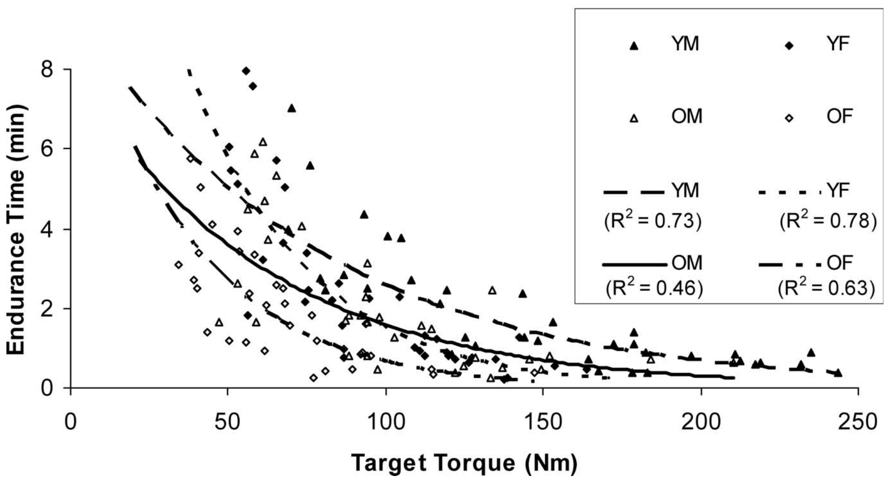


Figure 4. Relationships between endurance time and target torque fitted using exponential curves for (a) shoulder abduction and (b) torso extension. YM = younger male; YF = younger female; OM = older male; OF = older female.

trend was observed ($p = 0.10$) with almost overlapping curves between younger and older females. For the torso, a significant difference between both age groups was found, with a distinct upward shift in the younger group.

3.3. *Rate of maximum voluntary contraction decline*

Both experiments induced substantial reductions in maximum strength, ranging from about 4% per min to 40% per min. These declines were significantly greater at higher effort levels, with rates at 70% MVC three to four times greater than those at 30% MVC. Older participants had lower rates of MVC decline (about 30% for the shoulder and 14% for the torso) across effort levels, but the age effect was significant only for the shoulder (figure 5), not for torso. While a gender effect was not observed at the shoulder, its interaction with age was significant, as demonstrated by the smaller differences found between older male and female participants.

3.4. *Electromyographic-based measures*

During shoulder abduction, rates of EMG-amplitude increase varied between 4% per min and 37% per min. The effects of age and gender were not significant, and no two-way interactions were found. EMG spectral measures (MnPF and MdPF) obtained during shoulder abduction exhibited consistently decreasing trends. Older participants had significantly less rapid spectral changes, with a mean difference of roughly 27% between older and younger. The interactive effect of age × effort level was significant, with greater age-associated differences as effort level increased (figure 6). Effects of gender were not evident.

For torso extension, no significant differences were found in EMG changes between the left and right low-back muscles for either amplitude or spectral measures. Further analyses were therefore based on mean values of the bilateral data. Although younger individuals generally had more rapid changes in EMG amplitude, age effects were not significant for the multifidus and only approached significance for the longissimus

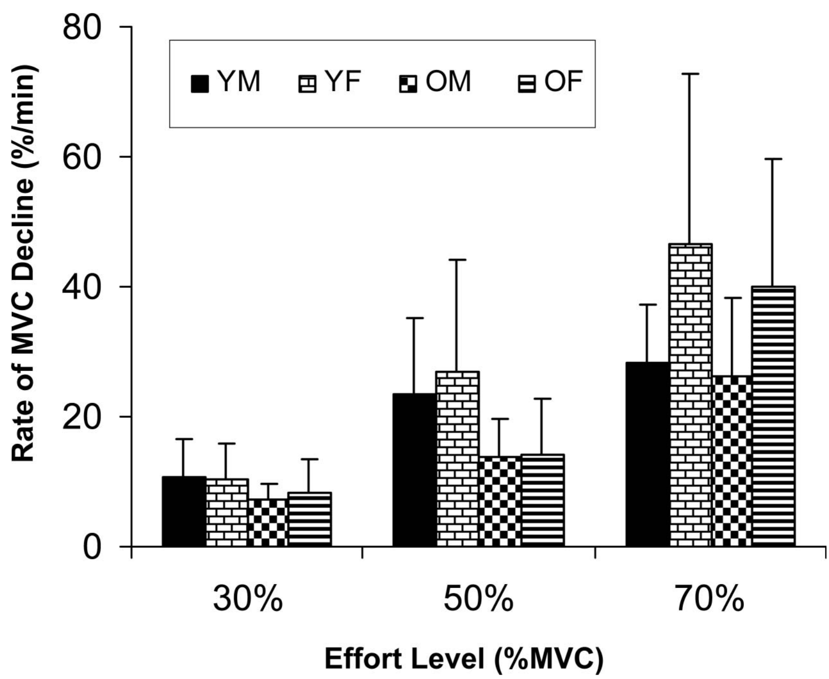


Figure 5. Rates of maximum voluntary contraction (MVC) decline for shoulder abduction, with significant effects of age, effort level and age × gender. Error bars represent standard deviations. YM = younger male; YF = younger female; OM = older male; OF = older female).

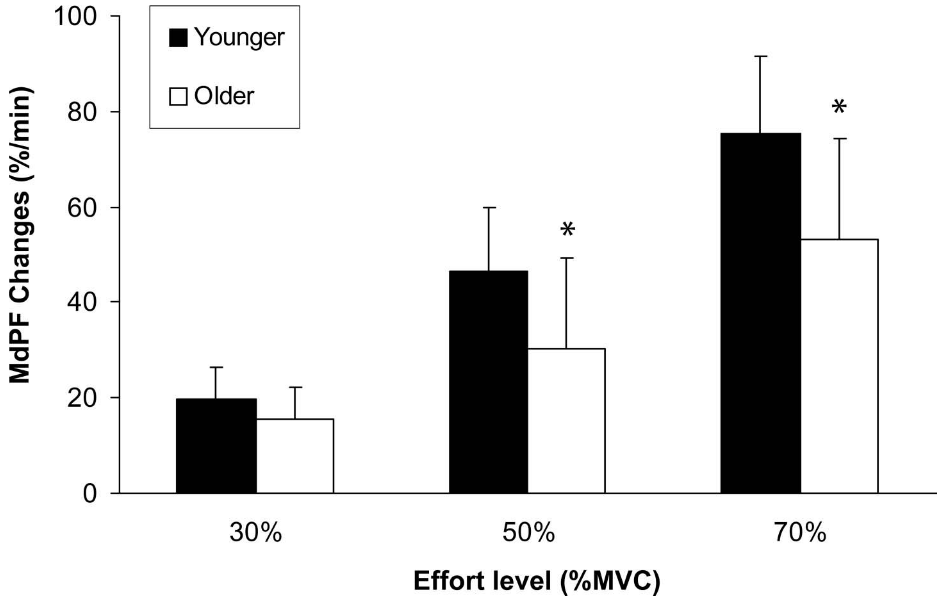


Figure 6. Electromyographic median power frequency (MdPF) changes during shoulder abduction (results similar for mean power frequency), with a significant effect of age × effort level. Error bars represent standard deviations and * indicates significant differences. YM = younger male; YF = younger female; OM = older male; OF = older female).

($p = 0.07$). For both muscles, the interactive effect of age × effort level approached significance ($p = 0.07$). No effects of gender or interactions with gender were present. With regard to changes in EMG spectral measures, the two torso muscles showed similar patterns (figure 7). Less rapid rates of decline were observed for older individuals (about half of those for younger participants). The age × effort level interaction was significant, with greater discrepancies in the slopes between younger and older groups observed as effort levels increased. While an effect of gender as a main effect was not found, its interactive effect with age was significant. This interaction effect showed significantly greater rates of decline for younger males than for the other three groups.

3.5. *Strength recovery*

During the recovery period, a substantial proportion of muscle strength was regained within the first few minutes (figure 8). The magnitude of strength loss at the cessation of both exercises was significantly lower for the older group than for the young, but the difference became non-significant after 10 min for the shoulder abduction and after 2 min for the torso extension. Roughly 75% of trials could be well-fitted using an exponential model; the remaining data showed linear or non-monotonic trends and these were almost equally distributed across age and gender groups. It should be noted that only the well-fitted trials were analysed here. There were no significant age or gender effects on recovery rates in either experiment. The effect of effort level approached significance ($p = 0.07$) for the torso, but only a trend was observed for the shoulder ($p = 0.12$). The effort level effect in both experiments indicated a tendency for faster recovery rates following exercises at lower effort levels.

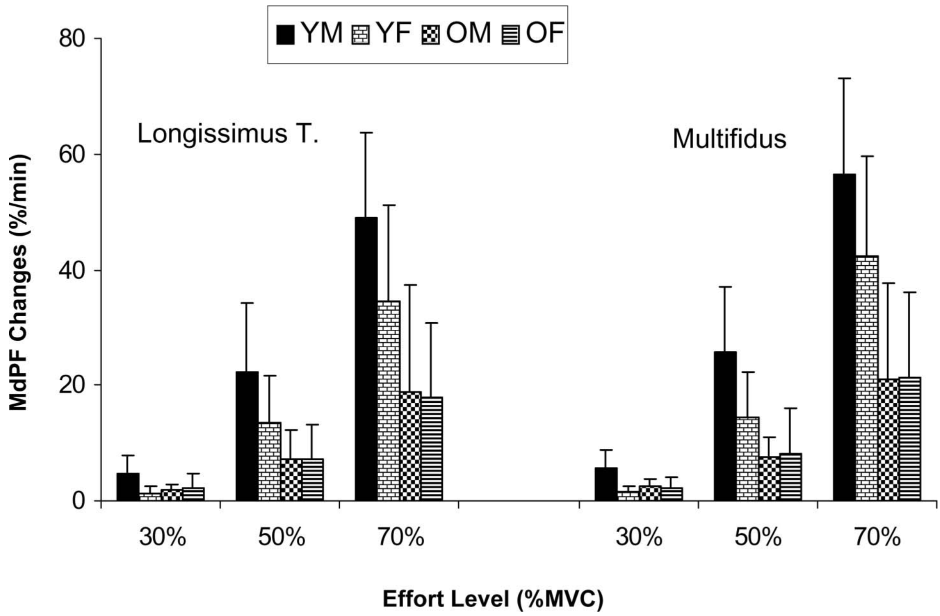


Figure 7. Rates of decrease of electromyographic median power frequency (MdPF) during torso extension (results similar for mean power frequency), with significant effects of age × gender and age × effort level. Error bars represent standard deviations. YM = younger male; YF = younger female; OM = older male; OF = older female; MVC = maximum voluntary contraction.

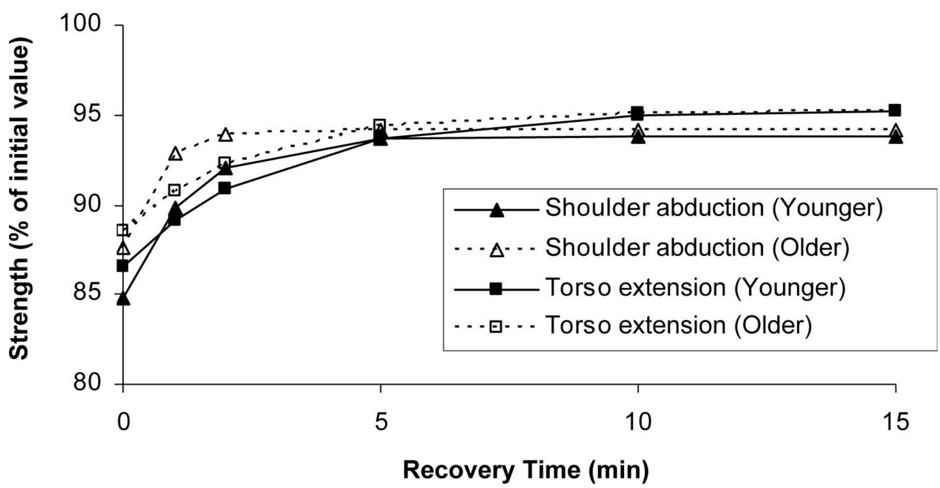


Figure 8. Strength recovery following shoulder abduction and torso extension. Equations for fitted curves are as follows.
Shoulder abduction – Younger: $S = 93.8 - 8.99\ e^{-0.82 * t}$; Older: $S = 94.2 - 6.57\ e^{-1.58 * t}$, Torso extension – Younger: $S = 95.2 - 8.67\ e^{-0.35 * t}$; Older: $S = 95.3 - 6.69\ e^{-0.41 * t}$, where S = strength (%initial), t = time (min).

4. Discussion

The present study aimed to quantify the effects of age on muscle endurance, fatigue and recovery after sustained isometric efforts using two different exercises (shoulder abduction and torso extension). The major findings suggest that older individuals (55–65 years), although exhibiting substantially lower muscle strength, have distinctly increased muscle endurance and less rapid development of local fatigue as compared to younger individuals at comparable levels of relative effort. Differences due to aging were generally more substantial and more consistent during shoulder abductions than lumbar extensions, suggesting a muscle dependency of these age effects.

4.1. *Muscle strength*

Older individuals had about 19% less initial (pre-fatigue) strength in shoulder abduction. This result is comparable to earlier reports using similar exercises and age ranges that showed a difference of 16% (Bäckman *et al.* 1995) and 23% (Hughes *et al.* 1999). A slightly greater difference (27%) in torso extension strength was found between the two age groups. This difference, however, is also comparable to the results of Viitasalo *et al.* (1985), who found that individuals aged 51–55 and 71–75 years had roughly 15% and 35% less torso extension strength, respectively, when contrasted with a younger group (31–35 years).

It is generally accepted that a decline in maximum strength with advancing age occurs after the fifth decade of life (Johnson 1982, Bemben *et al.* 1991, Bäckman *et al.* 1995). This strength decline with aging has been attributed to a reduction in both quality and quantity of excitable muscle mass (Larsson *et al.* 1979, Vandervoort and McComas 1986, Roos *et al.* 1999), primarily due to irreversible fibre damage and a permanent denervation (Brooks and Faulkner 1994, Lexell 1995, Payne and Delbono 2004). The fact that the decline in MVCs in this study differs between muscles is in accordance with earlier observations of variability across muscles (Bemben *et al.* 1991, Lynch *et al.* 1999). Muscle dependency in the age effect may be due, in part, to a more substantial reduction in the use of lumbar extensor muscles with aging (or less habitual use) as compared to the shoulder musculature (Garg 1991, Jørgensen 1997).

Given that the present study focused on endurance and fatigue during participant-specific (relative) effort levels, the results clearly depended on the ability of each participant to exert maximal efforts consistently across experimental sessions. Regardless of age, this requirement appears to be fulfilled by well-trained and motivated healthy individuals (Vandervoort and McComas 1986, De Serres and Enoka 1998, Kent-Braun *et al.* 2002, Lanza *et al.* 2004). More specifically, reports by Kent-Braun *et al.* (2002) and Lanza *et al.* (2004) also indicated no substantial age-related effects in the ability to maximally activate muscles even at the cessation of a fatiguing task. Further evidence of MVC quality is provided by the repeatability of MVCs across days obtained here, as shown by excellent ICC values and relatively small SEMs and CVs.

4.2. *Age-related differences in muscle endurance and fatigue*

The findings related to the presence of age effects in isometric endurance time during shoulder exercise confirmed similar results previously reported (Larsson and Karlsson 1978, Chan *et al.* 2000, Bilodeau *et al.* 2001b). Age-related increases in endurance are generally argued to occur as a result of a change in the proportion of muscle fibre types (i.e. increased type I:type II ratio) that occurs with aging (e.g. Larsson and Karlsson 1978), which in turn is a consequence of selective atrophy of fast-twitch fibres (Lexell 1995). The greater proportion of slow-twitch fibres may result in less lactate accumulation during the type of prolonged efforts studied here (Larsson and Karlsson 1978). It should be noted that muscle metabolic aspects such as substrate availability and oxidative capacity may also affect muscle fatiguability (Bemben 1998), and aging processes affecting such metabolic activities have been suggested to vary across muscles depending on muscle morphology, utilization of the muscle and metabolic demands (Pastoris *et al.* 2000). It can only be speculated that this variance in fibre composition may explain the disparity in the age-related effects on fatiguability between shoulder and torso muscles obtained in the present study.

The older group also showed slower declines in EMG spectral measures and similar findings have been reported in several earlier studies (Merletti *et al.* 1992, Yamada *et al.* 2000, Merletti *et al.* 2002). This effect is likely a consequence of the higher proportion of slow-twitch fibres in older muscles (Merletti *et al.* 2002, Macaluso and De Vito 2004). As noted, a muscle with a predominance of slow-twitch fibres has a lower likelihood of lactate accumulation and acidosis (Brody *et al.* 1991, Kupa *et al.* 1995, Yamada *et al.* 2000). Therefore, a lower rate of decline in muscle fibre conduction velocity and EMG spectral measures can be expected (Mannion *et al.* 1998, Merletti *et al.* 2002). In addition, an interactive age × effort level was found in the present study, with a more considerable difference observed at higher effort levels. As speculated by Bazzucchi *et al.* (2005), this phenomenon could be explained by a relatively greater recruitment of fast-twitch muscle fibres among younger individuals at higher effort levels. In contrast to EMG spectral measures, less consistent results were obtained for EMG amplitude (RMS). This finding may be partly explained by age-related variations in motor unit behaviours in generating different levels of effort (Gerdle *et al.* 1997).

A delayed development of fatigue among older individuals was also supported by the lower rates of MVC decline, with this measure often considered as the 'gold standard' for fatigue assessment (Vøllestad 1997). Rates of MVC decline were lower for the older group in both experiments, although the effect was only substantial for the shoulder. In some cases, the effects of age on fatigue were moderated by gender (age × gender interaction). This interactive effect was found to be substantial for rates of MVC decline during shoulder abduction and for rates of EMG spectral changes during torso extension. Both muscles demonstrated greater gender-related effects for younger subjects. The existence of an age × gender interaction effect on muscle fatiguability has previously been documented by Ditor and Hicks (2000) and Hunter *et al.* (2004), although the effect was found for different measures. This interactive effect could be due to a mixed influence of muscle histology, sex hormones and muscle capillarization (Ditor and Hicks 2000). However, it is not clear why this effect was inconsistent across muscles and across dependent measures.

4.3. *Muscle endurance at relative vs. absolute loads*

It should be noted that effort levels examined here were relative (i.e. normalized against an individual's MVC), and it is therefore not known whether the observed age effects on endurance might also be present if absolute effort levels had been used. As indicated by Larsson and Karlsson (1978), an age-related decline in muscular endurance may be expected at comparable absolute loads due to age-associated reduced muscle strength resulting in an increased relative load in older individuals. Interestingly, however, a recent study using strength matched individuals to examine age-associated difference during sustained elbow flexion showed otherwise (Bazzucchi *et al.* 2005). Although a somewhat small cohort of subjects was recruited (six per age group), older individuals were found to have more resistance to fatigue based on endurance time and EMG measures. In contrast, the present study involved a relatively large number of participants with a goal of minimizing several participant-related confounding factors and increasing external validity.

The results in this study also allowed for examination of the relationships between endurance time and absolute torque, which were found to differ between muscles (as shown in figure 4). During shoulder abductions, the results suggest a marginal effect of age and similar abilities between younger and older females in performing the task, even at an absolute load. However, the results were different for the torso, where lower endurance times were found among older individuals at a similar load magnitude. These results, again, support the existence of muscle dependency in the age effect on muscle performance that may stem from differences between the shoulder and torso muscles in terms of muscle fibre type composition and atrophy rate. Such a muscle dependency should be considered in real world applications, for example, in designing appropriate tasks for older individuals.

4.4. *Age effects on strength recovery*

For both experiments, muscle strength was substantially regained within the first few minutes after cessation of activity. Several studies have found similar exponential patterns of strength recovery following a sustained effort (e.g. Clarke and Stull 1969, Elfving *et al.* 2002) and this pattern has also been found for EMG-based parameters and subjective ratings of perceived fatigue (Baker *et al.* 1993, Elfving *et al.* 2002). The present results indicate that age-related effects on the rate of strength recovery from sustained isometric exercise may be only marginal. Both age groups also demonstrated similar incomplete strength recovery (approx. 95%) at 15 min of recovery. Non-significant age-related effects on recovery rates have previously been reported after fatiguing elbow flexions at intermittent (Allman and Rice 2001) and at maximum (Bilodeau *et al.* 2001a) efforts. It appears that recovery from metabolic inhibition, which is mainly responsible for fatigue during a short sustained contraction, may not show age-related effects in the present study because of the use of normalized loads (Allman and Rice 2001). Different age effects might be expected after a longer duration exercise, using lower effort levels or a different exercise type, since such efforts might result in substantial peripheral failure at the level of excitation–contraction coupling (Baker *et al.* 1993).

4.5. *Task design Implications*

Results of this study highlight the importance of carefully assigning tasks to workers of different ages. While older workers may not have the required capacity for physically challenging tasks, they may be able to perform much lighter tasks for substantially longer periods of time. This approach also ensures job requirements that are well within workers' capacity, which in the long term may reduce the risks of musculoskeletal problems and symptoms. Effort level and gender were also found to influence the relationship between aging and local fatigue. An interaction effect between age $\times$ effort level implies that a relatively small increase in external workload, for example, may have more severe fatigue responses among younger vs. older workers. Similarly, the presence of an age × effort level interaction, although only found in a subset of measures, suggests that tasks assigned to younger and older female workers may not result in substantial performance differences, compared to circumstances where such tasks are allocated to younger and older male individuals. In short, ergonomists should consider these task and individual factors simultaneously when designing/evaluating occupational activities. Finally, as aging effects seem to be muscle dependent, muscle characteristics (e.g. habitual use and fibre type composition) also need to be taken into account. For instance, tasks requiring substantial levels of shoulder exertion may be more appropriate for older workers than ones involving the torso musculature.

4.6. *Study limitations*

A few limitations in the present study warrant discussion. Pure isometric efforts in a controlled posture, as studied here, may have little relevance in terms of the demands of daily living or occupational tasks. Instead, muscle activities are more typically performed dynamically with different postures adopted and different muscles activated with varying motor unit recruitment strategies. The use of isometric efforts, however, allowed for control of numerous sources of variability associated with dynamic efforts and ongoing work is addressing age effects using repetitive isokinetic efforts of the same muscles. Only two tasks were examined in this study, involving a limited number of muscles. As noted above, these tasks were selected because of differences in fibre type composition and function of the muscles involved. Results obtained here may therefore represent extreme cases of muscle dependency in the influence of age on muscular performance. During shoulder abductions, only the middle deltoid was monitored via EMG. Other synergistic muscles (e.g. supraspinatus) may also be involved during such exercises and could provide additional information about fatigue development, but recording the responses of such synergistic muscles would require more complicated signal acquisition procedures. Sole focus on the deltoid muscle EMG was based on its assumed dominant contribution to torque generation during these tasks.

5. Conclusions

Age is a critical factor affecting an individual's physical capacity. Compared to younger participants, older individuals exhibited decreased maximum muscular strength, longer endurance times and slower progressions of local fatigue, but showed little difference in rates of recovery. With regard to fatigue, the age effect was shown to be influenced by effort level, with more pronounced effects observed as the workload increased. Age effects also appear to be muscle dependent, with more substantial differences found at the middle deltoid when compared to lumbar extensor muscles. Effects of gender were found to be less substantial than age, but an interactive effect of gender with age on fatigue was found in some cases. Further work is warranted to determine if similar effects are present among other muscles, among different age groups and during more complex dynamic efforts.

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