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TITLE: Evaluation of Spine Health and Spine Mechanics in Servicemembers with Traumatic Lower Extremity Amputation or Injury

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RECIPIENT: Henry M. Jackson Foundation
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14. ABSTRACT

Low back pain (LBP) is a clinically important secondary impairment following lower-extremity trauma, with an estimated prevalence as high as 52-80%. During gait, alterations in trunk motion following lower limb amputation likely impose distinct demands on trunk muscles to maintain equilibrium and stability of the spine. The overall objective of this research is to identify the relationship(s) between trunk motion with traumatic lower-extremity amputation/injury and LBP via changes in spine mechanics and spine health, two important factors associated with LBP risk. Using a novel set of clinical, experimental, and computational methods, we expect to demonstrate a positive association between abnormal spine mechanics (i.e., increased spinal loads), that overtime, negatively affect spine health and increase LBP risk among SMs with lower-extremity trauma. Preliminary results, to date, support our working hypothesis that altered trunk motions with extremity trauma contribute to increase spinal loads by 17-95% relative to able-bodied individuals. Experimental methods are operational and enrollment is currently open to obtain additional prospective data (6 complete data sets obtained). We expect to show a positive association between elevated spine loads and poor spine health, which will support the need for trunk-specific rehabilitation procedures to reduce long-term incidence and recurrence of low back pain.

15. SUBJECT TERMS

Low Back Pain; Intervertebral Disc; Inter-Segmental Motion; Spine Load; Spinal Alignment; Fluoroscopy; Finite Element Model

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1. **INTRODUCTION:** Narrative that briefly (one paragraph) describes the subject, purpose and scope of the research.

Linking lower-extremity amputation/injury with low back pain (LBP) risk via biomechanical theory suggests that altered and asymmetric trunk kinematics and corresponding passive spinal tissue and trunk neuromuscular responses alter spine mechanics such that would, over time, adversely affect spine health. Therefore, the overall objective of this study is to investigate such relationships through cross-sectional evaluations of spine health and spine mechanics in persons with lower-extremity amputation/injury (with and without LBP) and uninjured controls.

2. **KEYWORDS:** Provide a brief list of keywords (limit to 20 words).

Low Back Pain; Intervertebral Disc; Inter-Segmental Motion; Spine Load; Spinal Alignment; Fluoroscopy; Finite Element Model

3. **ACCOMPLISHMENTS:** The PI is reminded that the recipient organization is required to obtain prior written approval from the awarding agency Grants Officer whenever there are significant changes in the project or its direction.

What were the major goals of the project?
List the major goals of the project as stated in the approved SOW. If the application listed milestones/target dates for important activities or phases of the project, identify these dates and show actual completion dates or the percentage of completion.

Specific Aim 1: Quantify lumbar spinal alignment and inter-segmental vertebral motions with traumatic lower-extremity amputation.
Major Task 1: Obtain IRB and HRPO approvals.
Target Date: by April 2015
Actual Date: April 24, 2015 (IRB approval) / June 26, 2015 (HRPO approval)
Major Task 2: Complete biomechanical data collections, analysis, and interpretations.
Target Dates: Months 6-24 (15% complete)
Additional Milestones: One abstract presented and one manuscript submitted.
Specific Aim 2: Quantify alterations in spine mechanics (loading) with traumatic lower-extremity amputation.
Major Task 3: Estimate spinal loads using collected biomechanical data as inputs into the finite element model of the lumbar spine.
Target Dates: Months 6-24 (10% complete)
Additional Milestones: One abstract presented and one manuscript published.
Specific Aim 3: Determine associations between spine loading and current spine health with traumatic lower-extremity amputation.
Major Task 4: Conduct physical spinal examinations.
Target Dates: Months 6-24 (15% complete)
Major Task 5: Obtain magnetic resonance images of the lumbar spine for quantitative evaluation of lumbar disc health.
Target Dates: Months 6-24 (0% complete)
Major Task 6: Author manuscript on entire study.
Target Dates: Months 30-36 (0% complete)
Additional Milestones: One abstract presented and one manuscript submitted.

What was accomplished under these goals?

For this reporting period describe: 1) major activities; 2) specific objectives; 3) significant results or key outcomes, including major findings, developments, or conclusions (both positive and negative); and/or 4) other achievements. Include a discussion of stated goals not met. Description shall include pertinent data and graphs in sufficient detail to explain any significant results achieved. A succinct description of the methodology used shall be provided. As the project progresses to completion, the emphasis in reporting in this section should shift from reporting activities to reporting accomplishments.

During the second year of this award, work was performed under major tasks 2-6. Specifically, prospective data collections continue in the areas of biomechanical and clinical assessments focused on the trunk and spine to identify potential relationships with low back pain risk factors. Biomechanical assessments include overground gait analyses with a focus on kinematics of the trunk and spine, as well as trunk muscle activity recorded using surface EMG. In addition, we are also capturing a more comprehensive understanding of current/recent history of LBP and its impact on daily life and functional activities- including the NIH Task Force's LBP Questionnaire and a legacy LBP questionnaire (Oswestry Disability Index).

Significant/key findings thus far include (see appendices for additional information in published materials):

- The coordination / motions between the trunk and pelvis with vs. without LLA are associated with ~31-55, 41-83, and 3-14% larger external demands on the lower back in the sagittal, coronal, and transverse planes, respectively

- Joint contact forces within the spine are increased with LLA; notably, largest increases (up to ~65% relative to uninjured individuals) were found in joint compressive forces owing to a complex pattern and increased (6-80%) activation of trunk muscles

- Peak compressive, lateral, and anteroposterior shear loads generally increased with increasing walking speed. However, increases in compression and lateral shear with increasing walking speed were larger among the persons with vs. without LLA, particularly in lateral shear at the fastest speed. In contrast, peak anteroposterior shear decreased with increasing walking speed among persons with LLA.

- Given that biomechanical factors are just one component of risk for LBP onset or recurrence (see Appendix5), additional psycho-social factors appear to modulate risk for LBP among persons with LLA. The specific results for this are currently being tabulated and are thus not yet available.

Other achievements:

Within the last 2-3 months, support staff have been hired, both of which are now on-site full time to support this study.. Additionally, to improve eventual clinical translation, we will be submitting soon a modification to include several clinic-based strength and endurance tests to supplement and connect the biomechanical and clinical evaluations. Briefly, these include hip abduction strength (isometric and eccentric), as well as bilateral hip bridge measurements. These metrics have been purported to play a more direct role in the altered trunk motions observed during gait and thus may be easily modifiable in future clinical efforts.

What opportunities for training and professional development has the project provided?
If the project was not intended to provide training and professional development opportunities or there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe opportunities for training and professional development provided to anyone who worked on the project or anyone who was involved in the activities supported by the project. "Training" activities are those in which individuals with advanced professional skills and experience assist others in attaining greater proficiency. Training activities may include, for example, courses or one-on-one work with a mentor. "Professional development" activities result in increased knowledge or skill in one's area of expertise and may include workshops, conferences, seminars, study groups, and individual study. Include participation in conferences, workshops, and seminars not listed under major activities.

Under the subaward to the University of Kentucky, Dr. Bazrgari and I are providing mentorship to a PhD student (Iman Shojaei). Beyond that, the project was not necessarily intended to provide training or professional development opportunities; however, the hiring of Dr. Butowicz (see below) as a post-doctoral researcher allows additional training and mentorship opportunities.

How were the results disseminated to communities of interest?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe how the results were disseminated to communities of interest. Include any outreach activities that were undertaken to reach members of communities who are not usually aware of these project activities, for the purpose of enhancing public understanding and increasing interest in learning and careers in science, technology, and the humanities.

To date, preliminary results have been disseminated at the 7th World Congress of Biomechanics as a podium presentation to an international audience of biomechanics experts. This presentation resulted in a scientific article now published in the journal Clinical Biomechanics (Appendix1), as well as a poster presentation at the 2016 MHSRS meeting (see Appendix2). More recently, we were also invited to write a review article that focuses on biomechanical risk factors for secondary health conditions after limb loss- this is now published in the journal Advanced Wound Care (Appendix3). The PI was invited to speak at the 2^{nd} annual workshop for spinal loads and deformations in Germany following an abstract submission (see Appendix4)- this will be presented orally and published as a full manuscript in a special issue of the Journal of Biomechanics in May 2017. Finally, work as part of this award has identified avenues to capture additional risk factors for LBP, and the literature review that occurred has since resulted in an additional review article (Appendix5). Additional avenues of dissemination will be pursued as new data continues to be collected in Year 3 of this award, including abstracts for presentation at MHSRS and the American Society of Biomechanics, and associated full length manuscripts.

Describe briefly what you plan to do during the next reporting period to accomplish the goals and objectives.

We will continue making substantial efforts to meet recruitment targets in the first 6 months of Year 3 such that summative data in both areas (i.e., biomechanical and clinical) can be interpreted and disseminated to all appropriate audiences. We will also collect 3D segmental kinematics using biplanar fluoroscopy in Dr. Tashman's new lab to compare to the 2D lumbar kinematics captured at WRNMMC.

4. **IMPACT:** Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as a result of the project relative to:

What was the impact on the development of the principal discipline(s) of the project?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe how findings, results, techniques that were developed or extended, or other products from the project made an impact or are likely to make an impact on the base of knowledge, theory, and research in the principal disciplinary field(s) of the project. Summarize using language that an intelligent lay audience can understand (Scientific American style).

Preliminary analyses of data collected thus far continue to support our working hypothesis that altered trunk motion with lower extremity trauma contributes to increase loads within the spine. As noted previously in this report, the following key findings have been identified thus far:

- The coordination / motions between the trunk and pelvis with vs. without LLA are associated with ~31-55, 41-83, and 3-14% larger external demands on the lower back in the sagittal, coronal, and transverse planes, respectively

- Joint contact forces within the spine are increased with LLA; notably, largest increases (up to ~65% relative to uninjured individuals) were found in joint compressive forces owing to a complex pattern and increased (6-80%) activation of trunk muscles

- Peak compressive, lateral, and anteroposterior shear loads generally increased with increasing walking speed. However, increases in compression and lateral shear with increasing walking speed were larger among the persons with vs. without LLA, particularly in lateral shear at the fastest speed. In contrast, peak anteroposterior shear decreased with increasing walking speed among persons with LLA.

- Given that biomechanical factors are just one component of risk for LBP onset or recurrence (see Appendix5), additional psycho-social factors appear to modulate risk for LBP among persons with LLA. The specific results for this are currently being tabulated and are thus not yet available.

Collectively, these results strongly support biomechanical factors in the development or recurrence of LBP secondary to lower limb loss. As the dataset continues to increase, we will start to assess relationships between these factors and the current health status/impact of LBP, as such relationships will help identify specific interventions (e.g., trunk-focused movement retraining) that may ultimately help mitigate the high prevalence and burden of LBP among this cohort in the longer term.

What was the impact on other disciplines?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe how the findings, results, or techniques that were developed or improved, or other products from the project made an impact or are likely to make an impact on other disciplines.

Nothing to Report.

What was the impact on technology transfer?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe ways in which the project made an impact, or is likely to make an impact, on commercial technology or public use, including:

- *transfer of results to entities in government or industry;*
- *instances where the research has led to the initiation of a start-up company; or*
- *adoption of new practices.*

Nothing to Report.

What was the impact on society beyond science and technology?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe how results from the project made an impact, or are likely to make an impact, beyond the bounds of science, engineering, and the academic world on areas such as:

- *improving public knowledge, attitudes, skills, and abilities;*
- *changing behavior, practices, decision making, policies (including regulatory policies), or social actions; or*
- *improving social, economic, civic, or environmental conditions.*

Our results to date support a prevailing theory that altered trunk (spinal) motions among persons with lower-extremity trauma increase risk for the onset and/or recurrence of LBP. As we continue building evidence for this theory, there is likely to be a strong case for interventional approaches aimed at controlling trunk motions and spinal loads during rehabilitation. While that is specific to one patient population, these relationships may advance overall public knowledge regarding such a common and impactful musculoskeletal disorder. Over time, this will reduce the substantial economic costs associated with its treatment and promote enhancements in psychological health and overall quality of life.

5. **CHANGES/PROBLEMS:** The Project Director/Principal Investigator (PD/PI) is reminded that the recipient organization is required to obtain prior written approval from the awarding agency Grants Officer whenever there are significant changes in the project or its direction. If not previously reported in writing, provide the following additional information or state, "Nothing to Report," if applicable:

Changes in approach and reasons for change
Describe any changes in approach during the reporting period and reasons for these changes. Remember that significant changes in objectives and scope require prior approval of the agency.

As briefly mentioned above, we will be submitting a (minor) modification to include a few additional clinically administered strength and endurance tests to bolster the biomechanical evaluations and improve eventual translation.

Actual or anticipated problems or delays and actions or plans to resolve them
Describe problems or delays encountered during the reporting period and actions or plans to resolve them.

Nine participants with lower limb amputations have been recruited; 5 completed all testing, 4 are scheduled to complete the testing within the next 2-3 weeks. While somewhat low relative to the recruitment target, we have ramped up recruitment efforts now that additional support personnel are finally in place. We have also intentionally not yet recruited the uninjured comparison population (~ 1/3-1/2 of the total sample), as we plan to anthropometrically and demographically match these individuals to those with lower-extremity trauma to minimize additional confounding when possible

Changes that had a significant impact on expenditures
Describe changes during the reporting period that may have had a significant impact on expenditures, for example, delays in hiring staff or favorable developments that enable meeting objectives at less cost than anticipated.

Nothing to report.

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents
Describe significant deviations, unexpected outcomes, or changes in approved protocols for the use or care of human subjects, vertebrate animals, biohazards, and/or select agents during the

reporting period. If required, were these changes approved by the applicable institution committee (or equivalent) and reported to the agency? Also specify the applicable Institutional Review Board/Institutional Animal Care and Use Committee approval dates.

Significant changes in use or care of human subjects

No significant changes to report. As noted above, IRB/HRPO approval dates:

IRB approval granted on April 1, 2015 (formal approval documents were uploaded to IRBnet on April 24)
HRPO approval for WRNMMC was granted on June 26, 2015 (A-18549.1)
HRPO approval for University Kentucky was granted on June 29, 2015 (A-18549.2)
Walter Reed IRB official start date (permission to begin study): August 4, 2015
Walter Reed IRB continuing review date: February 23, 2016

Significant changes in use or care of vertebrate animals.

N/A

N/A

6. **PRODUCTS:** List any products resulting from the project during the reporting period. If there is nothing to report under a particular item, state "Nothing to Report."

- **Publications, conference papers, and presentations**
  Report only the major publication(s) resulting from the work under this award.

  Journal publications. *List peer-reviewed articles or papers appearing in scientific, technical, or professional journals. Identify for each publication: Author(s); title; journal; volume: year; page numbers; status of publication (published; accepted, awaiting publication; submitted, under review; other); acknowledgement of federal support (yes/no).*

Butowicz, C.M., Dearth, C.L., and **Hendershot, B.D.** Impact of traumatic extremity injuries beyond acute care: Movement considerations for resultant long-term secondary health conditions. *Advances in Wound Care*- Special Issue on Amputee Care and Rehabilitation (Under Review).

Farrokhi, S., Mazzone, B., Schneider, M.J., Gombatto, S., Highsmith, M.J., and **Hendershot, B.D.** Biopsychosocial model of low back pain with lower limb amputation: A framework for future consideration. *Disability and Rehabilitation* (Under Review).

Shojaei, I., **Hendershot, B.D.**, Wolf, E.J., and Bazrgari, B. (2016) Persons with Unilateral Transfemoral Amputation experience larger spinal loads during level-ground walking compared to able-bodied individuals. *Clinical Biomechanics* 32: 157-163.

Books or other non-periodical, one-time publications. *Report any book, monograph, dissertation, abstract, or the like published as or in a separate publication, rather than a periodical or series. Include any significant publication in the proceedings of a one-time conference or in the report of a one-time study, commission, or the like. Identify for each one-time publication: Author(s); title; editor; title of collection, if applicable; bibliographic information; year; type of publication (e.g., book, thesis or dissertation); status of publication (published; accepted, awaiting publication; submitted, under review; other); acknowledgement of federal support (yes/no).*

Pasquina, P.F., **Hendershot, B.D.**, and Isaacson, B.M. (2016) Secondary Health Effects of Amputation (Chapter 24) Atlas of Amputations and Limb Deficiencies: Surgical, Prosthetic, and Rehabilitation Principles, 4th Edition. American Academy of Orthopaedic Surgeons: Rosemont, IL.

Other publications, conference papers, and presentations. *Identify any other publications, conference papers and/or presentations not reported above. Specify the status of the publication as noted above. List presentations made during the last year (international, national, local societies, military meetings, etc.). Use an asterisk (*) if presentation produced a manuscript.*

Hendershot, B.D. (2016) Biomechanical risk factors for low back pain with extremity trauma. *The Military Health System Research Symposium (MHSRS), Kissimmee, FL, USA.*

Hendershot, B.D., Shojaei, I., and Bazrgari, B. Faster walking speeds differentially alter spinal loads among persons with traumatic lower limb amputation. *2nd International Workshop on Spine Loading and Deformation.* Julius Wolff Institute, Berlin, Germany. May 18-20, 2017.

- **Website(s) or other Internet site(s)**
  List the URL for any Internet site(s) that disseminates the results of the research activities. A short description of each site should be provided. It is not necessary to include the publications already specified above in this section.

Nothing to report.

- **Technologies or techniques**
  Identify technologies or techniques that resulted from the research activities. In addition to a description of the technologies or techniques, describe how they will be shared.

Nothing to report.

- **Inventions, patent applications, and/or licenses**
  Identify inventions, patent applications with date, and/or licenses that have resulted from the research. State whether an application is provisional or non-provisional and indicate the application number. Submission of this information as part of an interim research performance progress report is not a substitute for any other invention reporting required under the terms and conditions of an award.

Nothing to report.

- **Other Products**
  Identify any other reportable outcomes that were developed under this project. Reportable outcomes are defined as a research result that is or relates to a product, scientific advance, or research tool that makes a meaningful contribution toward the understanding, prevention, diagnosis, prognosis, treatment, and/or rehabilitation of a disease, injury or condition, or to improve the quality of life. Examples include:
  - *data or databases;*
  - *biospecimen collections;*
  - *audio or video products;*
  - *software;*
  - *models;*
  - *educational aids or curricula;*
  - *instruments or equipment;*
  - *research material (e.g., Germplasm; cell lines, DNA probes, animal models);*
  - *clinical interventions;*
  - *new business creation; and*
  - *other.*

Nothing to report.

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

What individuals have worked on the project?
Provide the following information for: (1) PDs/PIs; and (2) each person who has worked at least one person month per year on the project during the reporting period, regardless of the source of compensation (a person month equals approximately 160 hours of effort). If information is unchanged from a previous submission, provide the name only and indicate "no change."

Example:

Name: Mary Smith
Project Role: Graduate Student
Researcher Identifier (e.g. ORCID ID): 1234567
Nearest person month worked: 5
Contribution to Project: Ms. Smith has performed work in the area of combined error-control and constrained coding.
Funding Support: The Ford Foundation (Complete only if the funding support is provided from other than this award).

Name: Bradford Hendershot, PhD (no change)

Name: Babak Bazrgari, PhD (no change)

Name: Courtney Butowicz, PhD, CSCS
Project Role: Co-I
Researcher ID: NA
Nearest person month worked: 3
Contribution to Project: Dr. Butowicz joined the team in July 2015 as a post-doctoral researcher to support all aspects of the project. She has already assisted with maintaining study documentation, proposed several additional clinical tests, and assisted with the collection of data.

Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

If the active support has changed for the PD/PI(s) or senior/key personnel, then describe what the change has been. Changes may occur, for example, if a previously active grant has closed and/or if a previously pending grant is now active. Annotate this information so it is clear what has changed from the previous submission. Submission of other support information is not necessary for pending changes or for changes in the level of effort for active support reported previously. The awarding agency may require prior written approval if a change in active other support significantly impacts the effort on the project that is the subject of the project report.

As noted in the Year 2 Q3 report, in June 2016 the PI transitioned from his prior role as a contract employee with the Henry M. Jackson Foundation to a civilian Army employee with the DOD-VA Extremity Trauma and Amputation Center of Excellence. Dr. Hendershot is still located at Walter Reed National Military Medical Center and now also directs activities within the Biomechanics and Virtual Reality Laboratories. His effort and dedication to this project are unchanged.

What other organizations were involved as partners?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe partner organizations – academic institutions, other nonprofits, industrial or commercial firms, state or local governments, schools or school systems, or other organizations (foreign or domestic) – that were involved with the project. Partner organizations may have provided financial or in-kind support, supplied facilities or equipment, collaborated in the research, exchanged personnel, or otherwise contributed.
Provide the following information for each partnership:
<u>Organization Name:</u>
<u>Location of Organization: (if foreign location list country)</u>
<u>Partner's contribution to the project</u> (identify one or more)

- *Financial support;*
- *In-kind support (e.g., partner makes software, computers, equipment, etc., available to project staff);*
- *Facilities (e.g., project staff use the partner's facilities for project activities);*
- *Collaboration (e.g., partner's staff work with project staff on the project);*
- *Personnel exchanges (e.g., project staff and/or partner's staff use each other's facilities, work at each other's site); and*
- *Other.*

Nothing to report.

8. SPECIAL REPORTING REQUIREMENTS

COLLABORATIVE AWARDS: For collaborative awards, independent reports are required from BOTH the Initiating PI and the Collaborating/Partnering PI. A duplicative report is acceptable; however, tasks shall be clearly marked with the responsible PI and research site. A report shall be submitted to **https://ers.amedd.army.mil** for each unique award.

QUAD CHARTS: If applicable, the Quad Chart (available on https://www.usamraa.army.mil) should be updated and submitted with attachments.

9. APPENDICES: Attach all appendices that contain information that supplements, clarifies or supports the text. Examples include original copies of journal articles, reprints of manuscripts and abstracts, a curriculum vitae, patent applications, study questionnaires, and surveys, etc.

Appendix 1: Article published in *Clinical Biomechanics*
Appendix 2: Abstract for 2016 MHSRS meeting
Appendix 3: Article (now) published in *Advanced Wound Care*
Appendix 4: Abstract for 2nd annual spine loading and deformation workshop
Appendix 5: Article under review in *Disability and Rehabilitation*

Increased and asymmetric trunk motion during level-ground walking is associated with larger spinal loads in persons with unilateral transfemoral amputation

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Phone: (859) 257-1379. E-mail: babak.bazrgari@uky.edu. Fax: (859) 257-1856

Abstract Word Count: 228

Main Text Word Count: 3637

Number of Figures: 5

Number of Tables: 3

ABSTRACT

Background: During gait, alterations in trunk motion following lower limb amputation likely impose distinct demands on trunk muscles to maintain equilibrium and stability of the spine. However, trunk muscle responses to such changes in physical demands, and the resultant effects on spinal loads, have yet to be determined in this population.

Methods: Trunk and pelvic kinematics collected during level-ground walking from 40 males (20 with unilateral transfemoral amputation and 20 matched controls) were used as inputs to a kinematics-driven, nonlinear finite element model of the lower back to estimate forces in 10 global (attached to thorax) and 46 local (attached to lumbar vertebrae) trunk muscles, as well as compression, lateral, and antero-posterior shear forces at all spinal levels.

Findings: Trunk muscle force and spinal load maxima corresponded with heel strike and toe-off events, and were respectively 10-40% and 17-95% larger during intact vs. prosthetic stance in persons with amputation, as well as 6-80% and 26-60% larger during intact stance relative to controls.

Interpretation: In addition to larger individual muscle responses to overall increases and asymmetries in trunk motion during walking, co-activations of antagonistic muscles were needed to assure spine equilibrium in three-dimensional space, hence resulting in substantial increases in spinal loads. Knowledge of trunk neuromuscular adaptations to changes in task demands following amputation could inform rehabilitation procedures such to reduce long-term incidence or recurrence of low back pain.

Keywords: Amputation, Gait, Muscle forces, Spinal loads, Low back pain

HIGHLIGHTS:

- Persons with lower limb amputation walk with large and asymmetric trunk motion
- Spinal equilibrium and stability under such motions require large muscular response
- Larger trunk muscle forces contribute to increase compression and shear loads
- Repeated exposures to altered spinal loading may elevate low back pain risk

1. INTRODUCTION

The prevalence of low back pain (LBP) is considerably higher in persons with lower limb amputation (LLA) compared with able-bodied individuals (Friberg, 1984, Sherman, 1989, Sherman et al., 1997, Smith et al., 1999). As a secondary health-related concern, LBP is suggested to be the most important condition that adversely affects the physical performance and quality of life in persons with LLA (Ehde et al., 2001, Taghipour et al., 2009). Providing the projected increase in the number of people with LLA, it is important to investigate the underlying mechanism(s) responsible for the elevated prevalence of LBP in this cohort (Reiber et al., 2010, Devan et al., 2014).

Considering spine biomechanics, spinal loads are the resultant of interactions between internal tissue forces (primarily from muscles) and physical demands of a given activity on the lower back (Cholewicki and Mcgill, 1996, Calisse et al., 1999, Arjmand and Shirazi-Adl, 2005, Adams et al., 2007, Mcgill et al., 2014). During gait, increased and asymmetric trunk motion following LLA has been reported to impose higher physical demands on the lower back (Cappozzo and Gazzani, 1982, Hendershot and Wolf, 2014). Such an increase in physical demand of a common daily activity like walking would require larger responses from internal trunk tissues to assure equilibrium and stability of the spine, hence leading to larger spinal loads that would presumably increase the risk for LBP due to the repetitive nature of such activities (Adams et al., 2007).

There is limited information in the literature related to internal trunk tissue responses and resultant spinal loads during walking (Cappozzo et al., 1982, Cappozzo, 1983, Cappozzo, 1983, Khoo et al., 1995, Cheng et al., 1998, Callaghan et al., 1999, Yoder et al., 2015). All but two of these few earlier studies included relatively small sample sizes of able-bodied male participants and have reported spinal loads at either the L4-L5 or L5-S1 discs. The predicted pattern of spinal loads in these studies included symmetric local maxima occurring around heel strike and toe off within the gait cycle, with values ranging between 1.2 to 3.0 times body weight. The other two studies regarding internal tissue responses and resultant spinal loads during walking also include persons with LLA (Cappozzo and Gazzani, 1982, Yoder et al., 2015). Using kinematics data obtained from two subjects (one with transfemoral amputation and one with knee ankylosis), Cappozzo and Gazzani (1982) used a rigid link-segment model of the whole body to obtain mechanical demands of walking on the lower back. A simple muscle model was then used to calculate internal tissue responses and the resultant spinal loads. Contrary to the patterns of spinal loads observed in able-bodied individuals, the occurrence of local maxima among persons with LLA did not have a symmetric pattern. Rather, the maximum compression forces were larger at the instance of prosthetic vs. intact toe off (2-3.0 vs. 1.0 times body weight). Similar differences in patterns of trunk muscular responses during walking, and the resultant effect on spinal loads (but at much lower magnitudes), between persons with and without transtibial LLA have been recently reported by Yoder et al. (2015). Although these earlier studies highlight the impact of altered and asymmetric gait on loads experienced in the lower back, they were limited to small samples and/or a very simple biomechanical model of the lower back.

Using a relatively large sample size, along with a biomechanical model of the lower back with more bio-fidelity, the objective of this study was to investigate the differences in internal tissue responses, specifically muscle forces, and resultant spinal loads during level-ground walking between individuals with (n=20) and without (n=20) unilateral LLA. Considering that alterations in trunk motion following amputation impose higher (and asymmetric) physical demands on the lower back (Cappozzo and Gazzani, 1982, Hendershot and Wolf, 2014), it was hypothesized that compared to able-bodied individuals, persons with LLA will require larger muscle forces in the lower back to overcome the physical demands of walking while maintaining spinal stability and equilibrium. Such increases in trunk muscle forces would, in turn, result in larger spinal loads. A better knowledge of lower back biomechanics (i.e., in terms of spinal loads) among individuals with LLA can inform future development of effective clinical programs aimed at modifying lower back biomechanics such to mitigate LBP risk.

2. METHODS

2.1 Experimental study: Kinematic data collected in an earlier study were used in these analyses (Hendershot and Wolf, 2014). Briefly, full-body kinematics from 20 males with transfemoral amputation and 20 male able-bodied controls were collected using a 23-camera motion capture system during level-ground walking across a 15 m level walkway at a self-selected speed (mean ≈ 1.35 m/s; Table-1). Here, kinematic data of interest included three-dimensional pelvic and thorax motions that were collected by tracking markers positioned in the mid-sagittal plane over the S1, T10, and C7 spinous processes, sternal notch, and xiphoid; and bilaterally over the acromion, ASIS, and PSIS. All amputations were a consequence of traumatic injuries with a mean (standard deviation) duration of 3.1 (1.4) years since amputation. Main inclusion criteria were: (1) unilateral transfemoral amputation with no contralateral functional impairments, (2) daily use of a prosthetic device (≥1 year post-amputation), (3) no use of an upper-extremity assistive device (e.g., cane, crutches, walker), and (4) having no other musculoskeletal or neurologic problem, except amputation, that may affect gait results. Details of inclusion and exclusion criteria and other experimental methodology can be found in Hendershot and Wolf (2014). This retrospective study was approved by Institutional Review Boards of both University of Kentucky and Walter Reed National Military Medical Center.

Table-1 may be inserted here

2.2 Modeling study: The biomechanical model used to estimate trunk muscle responses and resultant spinal loads included a non-linear finite element (FE) model of the spine that estimated the required muscle forces to complete the activity using an optimization-based iterative procedure (Arjmand and Shirazi-Adl, 2005, Arjmand and Shirazi-Adl, 2006, Bazrgari et al., 2007, Bazrgari et al., 2008, Bazrgari et al., 2009, Arjmand et al., 2010). In this model, muscle forces are estimated such that equilibrium equations are satisfied across the entire lumbar spine. The finite element model included a sagittally symmetric thorax-pelvis model of the spine composed of six non-linear flexible beam elements and six rigid elements (Figure 1) (Arjmand and Shirazi-Adl, 2005, Bazrgari et al., 2008). The six rigid elements represented the thorax, and each of lumbar vertebrae from L1 to L5, while the six flexible beam elements characterized the nonlinear stiffness of each intervertebral disc between the T12 and S1 vertebrae. Intervertebral discs' stiffness were defined using nonlinear axial compression–strain relationships along with moment–rotation relationships in sagittal/coronal/transverse planes that were obtained from earlier numerical and experimental studies of lumbar spine motion segments (Yamamoto et al., 1989, Oxland et al., 1992, Shirazi-Adl et al., 2002). Upper-body mass and mass moments of inertia were distributed along the spine according to reported ratios (Zatsiorsky and Seluyanov, 1983, De Leva, 1996, Pearsall et al., 1996). Inter-segmental damping with properties defined based on earlier experimental studies were also considered using connector elements (Markolf, 1970, Kasra et al., 1992). The muscle architecture in the biomechanical model included 56 muscles (Fig. 1); 46 muscles connecting lumbar vertebrae to the pelvis (i.e., local muscles) and 10 muscles connecting thoracic spine/rib cage to the pelvis (i.e., global muscles) (Arjmand and Shirazi-Adl, 2005, Arjmand and Shirazi-Adl, 2006, Bazrgari et al., 2008, Bazrgari et al., 2008).

Figure 1 may be inserted here

To determine the required muscle forces for satisfaction of equilibrium across the entire lumbar spine, segmental kinematics in the lumbar region were required. Since only kinematics of the thorax and the pelvis were available from the experimental measurements, a heuristic optimization procedure (Figure 2) was used in the biomechanical model to determine a set of segmental kinematics in the lumbar region (i.e., from L1 to L5) such that the corresponding set of predicted muscles forces minimized a cost function (Shojaei and Bazrgari, 2014). The cost function used for this heuristic optimization procedure was the sum of squared muscle stress across all lower back muscles. Specifically, a set of possible segmental kinematics in the lumbar region that was within the reported range of motion of lumbar motion segments was initially prescribed on the FE model and the equations of motion were solved using an implicit integration algorithm inside an FE software (ABAQUS, Version 6.13, Dassault Systemes Simulia, Providence, RI). The outputs of equations of motion were three-dimensional moments at each spinal level, from T12 to L5, that were to be balanced by muscles attached to these same spinal levels. Because the number of attached muscles to these levels (i.e., 10 muscles in each level from T12 to the L4 and 6 muscles at L5) was more than the number of equilibrium equations (i.e., three at each vertebra), a local optimization problem was also solved for each level to obtain a set of muscle forces that minimize the aforementioned cost function only at that specific level (Arjmand and Shirazi-Adl, 2006). These local optimization procedures were performed using the Lagrange Multiplier Method. The above procedure was repeated inside the heuristic optimization for as many possible sets of segmental kinematics, determined using a genetic algorithm, until a set of segmental kinematics was obtained that meets the optimization criterion. The associated muscle forces with the optimal local kinematics were then used to estimate spinal loads at all lumbar levels. These spinal loads included compression forces, along with anterior-posterior and medio-lateral components of the shear forces, relative to the mid-plane of the intervertebral disc and at each lumbar level. The heuristic optimization procedure was developed in Matlab (The MathWorks Inc., Natick, MA, USA, version 7.13).

Figure 2 may be inserted here

2.3 Statistical analyses: Rather than comparing the predicted forces in all 56 muscles between the two groups, the summation of forces in global and local muscles were separately used for statistical analyses. Similarly, rather than comparing spinal loads at each level, levels with highest spinal loads (i.e., L4-L5 or L5-S1 for compression forces and L5-S1 for shear forces) were considered for subsequent statistical analyses. For each outcome measure, local maxima were extracted from the stance phase of each leg, resulting in the following values: 1) two peaks in the predicted global and local muscle forces (Fig. 3; Peak-1 at heel strike of the ipsilateral limb and Peak-2 at toe off the contralateral limb), 2) two peaks in the predicted compression forces (Fig. 4; Peak-1 at heel strike of the ipsilateral limb and Peak-2 at toe off the contralateral limb), and 3) one peak in each of the lateral (Fig. 5; at toe off of the contralateral limb), anterior (Fig. 5; at toe off of the contralateral limb), and posterior shear forces (Fig. 5; at heel strike of the ipsilateral limb). It is of note that the gait cycle was defined from right heel strike to subsequent right heel strike for controls, and from heel strike of the intact leg to next heel strike of the intact leg for persons with LLA. Prior to statistical analyses, all maxima were normalized with respect to total body mass. Furthermore, because there was no significant differences ($P>0.21$ from paired t-tests) in any of the aforementioned maxima between the right and left legs of controls, statistical analyses were performed using the mean values for the two legs of control group.

3. RESULTS

Mean sum of global and local muscle forces for both groups are depicted in Figure 3. Mean sum of maximum global muscle forces was 2.6 N/kg larger at heel strike of the intact vs. prosthetic limb among persons with LLA (Table 2); the sum of global muscle forces was only significantly larger at intact heel strike in persons with LLA than the corresponding value in controls. For local muscles at the instant of heel strike, there were no significant differences ($P>0.41$) within and between groups. At toe-off, the mean sum of maximum global muscle forces was 3.6 N/kg larger in intact vs. prosthetic limb stance among persons with LLA; this local maximum was also 5.6 N/kg larger in intact stance among persons with LLA than controls, but not significantly different between prosthetic stance relative to controls. For local muscles at the instant of toe-off, while there were no significant differences between the values in the stance phase of intact and prosthetic legs of persons with LLA, they were, respectively, 2.5 N/kg and 1.5 N/kg larger than the corresponding values in controls.

Figure 3 may be inserted here

Table-2 may be inserted here

Mean compression forces were 3.4 N/kg larger at heel strike of the intact vs. prosthetic leg among persons with LLA; the compression force at heel strike of the intact leg was also 4.8 N/kg larger than the corresponding value in controls, while there were no significant differences between the prosthetic leg of persons with LLA and the corresponding value in controls (Table 2). Mean compression force at toe off of the contralateral limb was similar between stance of the intact and prosthetic legs among persons with LLA, but were 8.6 N/kg (4.7 N/kg) larger during intact (prosthetic) leg stance than the corresponding value in controls.

Figure 4 may be inserted here

In the lateral direction, maximum shear forces were 4.3 N/kg larger in the stance phase of the intact vs. prosthetic leg among persons with LLA (Table 2). These were also 3.3 N/kg larger in the stance phase of intact leg of persons with LLA than the corresponding value in controls; there were no significant differences between the stance phase of prosthetic leg and that of controls. In the posterior direction, maximum shear forces among controls were 1.3 and 1.8 N/kg larger than the corresponding values in intact and prosthetic stance among persons with LLA, respectively. Maximum posterior shear forces were not different between intact and prosthetic stance among persons with LLA. In the anterior direction, maximum shear forces were 1.4 N/kg larger in the stance phase of the intact vs. prosthetic leg among persons with LLA; these were also 1.8 N/kg larger in the stance phase of the intact leg than the corresponding value in controls.

Figure 5 may be inserted here

4. DISCUSSION

In this study, trunk muscle responses to walking demands and the resultant spinal loads were estimated in individuals with and without unilateral LLA. It was hypothesized that individuals with LLA would require larger muscle forces to overcome the physical demands of walking while maintaining spinal equilibrium and stability, which would in turn result in larger spinal loads compared to individuals without amputation. The results obtained through computational simulations and subsequent statistical analyses confirmed our hypothesis. Higher trunk muscle forces and larger spinal loads on the lower back of individuals with unilateral LLA during walking may be in part responsible for the reported higher prevalence of LBP among persons with vs. without LLA.

The local maxima for muscle forces and the resultant spinal loads occurred at the instants of heel strike and toe off within the gait cycle. These time points also happen to correspond with the instances of large axial twist of the trunk (i.e., heel strike) and asymmetric trunk posture (i.e. toe off where there were relatively large motions in all three planes (Hendershot and Wolf, 2014)). In addition to individual muscle responses, co-activations of antagonistic muscles were needed under such trunk motions to assure spine equilibrium in three-dimensional space. The effects of such an increased and asymmetric motion on muscle forces is more evident when comparing the kinematics and associated muscle forces in the stance phase of intact and prosthetic legs among individuals with LLA. The increases in trunk motion and its asymmetry at instances of heel strike and toe off were more pronounced during the stance phase of the intact leg of persons with LLA, particularly at heel strike of the ipsilateral limb (Hendershot and Wolf, 2014), that resulted in much larger muscle forces during the stance phase of intact than prosthetic leg. Such an effect may also be a result of proximal compensations (e.g., hip-hiking) to assist with toe clearance (Michaud et al., 2000), or simply because these individuals feel more confident during intact (vs. prosthetic) stance to advance their center of mass.

The sum of forces in global muscles during the gait cycle was comparable with the sum of forces in the local muscles (Fig. 3). It should be mentioned, however, global muscles were the primary responders to activity demands during the first iteration of muscle force calculations in our model (i.e., the local loop in Fig. 2). As the effects of such global muscle forces were applied into the model, during the subsequent iterations, local muscles became activated to prevent buckling of the spine under the penalties of global muscle forces. If the summation of forces in global and local muscles is assumed to represent the required energy for respectively equilibrate and stabilize the spine, our results suggest that relatively equal amounts of energy were consumed to provide equilibrium and stability to the spine during walking. However with such an assumption, it seems that overcoming the equilibrium demands of walking impact the spinal loads of individuals with LLA more than overcoming its segmental stability demands when compared with able-bodied individuals. This observation is reflected in the sum of differences in mean global muscle forces (i.e., assumed to represent differences in equilibrium demands) between persons with and without LLA that was 955 N larger than the sum of differences in mean local muscle forces (i.e., assumed to represent differences in stability demands) between the same two groups. We should, however, emphasize that such interpretation is limited to assumptions made in our optimization-based method for estimation of muscle responses to activity demand and would require verification via measurement of muscle activity. A stabilizing response from local muscles as suggested here should occur sooner than equilibrating response from global muscles.

The predicted spinal loads for controls were in agreement (in terms of patterns and magnitudes) with those obtained in earlier studies (Cappozzo, 1983, Khoo et al., 1995, Cheng et al., 1998, Callaghan et al., 1999, Yoder et al., 2015). Depending on walking speed, the reported values of maximum compression force at the lower spinal level ranged between 1.0 to 2.95 times body weight for walking speeds ranging from 0.9 to 2.2 m/s (Table 3). The mean maximum compression force from these studies, along with average walking speed, were respectively ~ 1.94 times body weight at 1.4 m/s, which are comparable with our predictions of a maximum spinal load of ~ 1.85 times body weight for an average walking speed of ~1.35 m/s. Maxima in predicted compression forces in this study occurred around heel strike and toe off instances within the gait cycle, which are also consistent with reported timing of maximum compression forces in earlier studies: around toe off instants (Callaghan et al., 1999), within a short time interval around toe off (Cappozzo, 1983), right after the heel strike and before complete toe off (Cheng et al., 1998), and around 20% and 80% of walking cycle (Khoo et al., 1995).

Table-3 may be inserted here

The results obtained from individuals with unilateral LLA in this study were also consistent in pattern and magnitude with those reported by Cappozzo and Gazzani (Cappozzo and Gazzani, 1982). This earlier study reported spinal loads for two subjects (i.e., one with transfemoral amputation and one with knee ankylosis) during level-ground walking. The reported maxima of predicted compression forces for the person with LLA) ranged from 2 to 3 times body weight for walking speeds between 1.0 m/s and 1.5 m/s (Table 3), which is consistent with the range of maxima of predicted compression forces in this study (~ 2 to 2.6 body weight). In both studies, the maximum compression forces occurred during intact limb stance at the instance of prosthetic toe off. In a more recent study (Yoder et al 2015), much smaller maxima (i.e., ~ body weight) have been reported for maximum spinal loads among persons with transtibial LLA; though smaller maxima could be due, in part, to the relatively slower walking speed and/or more distal amputation.

The sample of persons with LLA in this study included young and physically fit members of the military with transfemoral amputations resulting from traumatic injuries. Thus, the results cannot be generalized to groups with other levels or etiologies of amputation. This cross sectional study also does not provide any information about lower back biomechanics in these individuals before the amputations, and history of LBP was not controlled in the participants, though those with current LBP were excluded from the study. Although we accounted for individual differences in trunk inertial properties in the non-linear FE model of spine, we used the same passive tissue properties for all subjects since we had no access to the subject-specific behavior of such tissues (i.e., ligaments, intervertebral discs, passive behavior of muscles and bony structures) for these participants. Furthermore, same heights were considered in the spine model for all subjects, though stature was not significantly different between groups.

5. CONCLUSION

Asymmetric and larger trunk motion of individuals with LLA during walking requires higher activation and co-activation of trunk muscles to assure equilibrium and stability of the spine, which in turn increase spinal loads. An elevated level of spinal loads during a basic activity of daily living like walking may increase risk of developing LBP, in particular due to the repetitive nature of such activity. It is imperative to investigate whether those with LLA consistently experiencing higher levels of spinal loads during other important activities of daily living (e.g., ascending and descending ramps or stairs) as a result of an alteration in internal tissue responses to activity demands. Such knowledge can inform future development of effective clinical programs aimed at reducing the risk for developing LBP via management of spinal loads during daily activities.

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TABLE AND FIGURE CAPTIONS

Table-1: Participant characteristics for the control (CTL) and lower limb amputation (LLA) groups. (Hendershot and Wolf, 2014).

Table-2: Mean (SD) predicted maximum muscle forces and resultant spinal loads.

Table-3: Reported values of maximum compression force (*body weight) at the lower spinal level.

Figure 1. Sagittal view of the biomechanical model including FE model of the spine and 56 trunk muscles (dimensions in mm). ICPL: iliocostalislumborum pars lumborum, ICPT: iliocostalislumbroum pars thoracis, IP: iliopsoas, LGPL: longissimusthoracis pars lumborum, LGPT: longissimusthoracis pars thoracis, MF: multifidus, QL: quadratuslumborum, IO: internal oblique, EO: external oblique and RA: rectus abdominus.

Figure 2. The process used to estimate muscle forces and spinal loads. Each set of possible segmental kinematics is generated using a genetic algorithm subjected to measured kinematics of thorax and pelvis as well as the reported values of lumbar segments' range of motion. The convergence in the local and global loops are achieved when the changes in respectively sum of predicted muscle forces in two consecutive local iterations and the value of the cost function of the heuristic optimization procedure in two consecutive global iterations are less than 1%.

Figure 3. Mean sum of forces in global (i.e., muscles attached to the thoracic spine – top) and local (i.e., muscles attached to the lumbar spine – bottom) muscles. CTL: control group, LLA: group with lower limb amputation.

Figure 4. Mean compression forces at mid-plane of the L4-L5 (top) and L5-S1 (bottom) intervertebral discs. CTL: control group, LLA: group with lower limb amputation.

Figure 5. Mean shear forces at the mid-plane of the L5-S1 in lateral (top) and antero-posterior (bottom) directions. CTL: control group, LLA: group with lower limb amputation. Positive shear force in lateral direction indicates force toward the right (intact) leg for controls (LLA) and positive shear force in antero-posterior direction indicate anterior direction.

Table-1: Participant characteristics for the control (CTL) and lower limb amputation (LLA) groups. (Hendershot and Wolf, 2014).

Variable	**CTL (n=20)**	**LLA (n=20)**
Age (year)	28.1 (4.8)	29.20 (6.70)
Stature (cm)	181.00 (6.10)	176.20 (6.70)
Body mass (kg)	83.90 (8.60)	80.60 (12.20)

Table-2: Mean (SD) predicted maximum muscle forces and resultant spinal loads.

Variable	**Control (n=20)**	**Transfemoral Amputation (n=20)**	
		Intact Stance	Prosthetic Stance
MUSCLE FORCES			
Global (thorax) – Peak 1 (N/kg)	7.7 (2.5)	10.4 (5.0) *	7.8 (3.0) †
Global (thorax) – Peak 2 (N/kg)	7.0 (2.6)	12.6 (5.2) *	9.0 (4.1) †
Local (lumbar) – Peak 1 (N/kg)	8.4 (2.0)	8.9 (2.1)	8.1 (1.7)
Local (lumbar) – Peak 2 (N/kg)	7.8 (1.4)	10.3 (3.1) *	9.3 (2.3) *
SPINAL LOADS			
Compression – Peak 1 (N/kg)	18.2 (3.4)	23.0 (5.8) *	19.6 (4.1) †
Compression – Peak 2 (N/kg)	16.8 (3.3)	25.4 (7.0) *	21.5 (4.8) *
Lateral Shear (N/kg)	5.5 (1.1)	8.8 (1.6) *†	4.5 (1.2)
Posterior Shear (N/kg)	3.7 (0.8)	2.4 (0.8) *	1.9 (0.6) *
Anterior Shear (N/kg)	4.2 (1.0)	6.0 (1.1) *	4.6 (0.9) †

* Significant difference relative to control

† Significant difference between intact vs. prosthetic

Table-3: Reported values of maximum compression force (*body weight) at the lower spinal level.

Study		Walking Speed (m/s)						
		0.90	1.00	1.20	1.35	1.50	1.70	2.20
Typical walking	Current study				1.85			
	Cappozzo, 1983		1.20		1.50		1.90	2.50
	Cheng et al., 1998		2.28	2.53		2.95		
	Khoo et al., 1995			1.71				
	Yoder et al., 2015	1.0						
Atypical walking	Current study				2.60			
	(Cappozzo and Gazzani, 1982) (amputation)		2.00		2.70	3.00		
	(Cappozzo and Gazzani, 1982) (knee ankylosis)		1.80			2.10		
	Yoder et al., 2015	1.0						

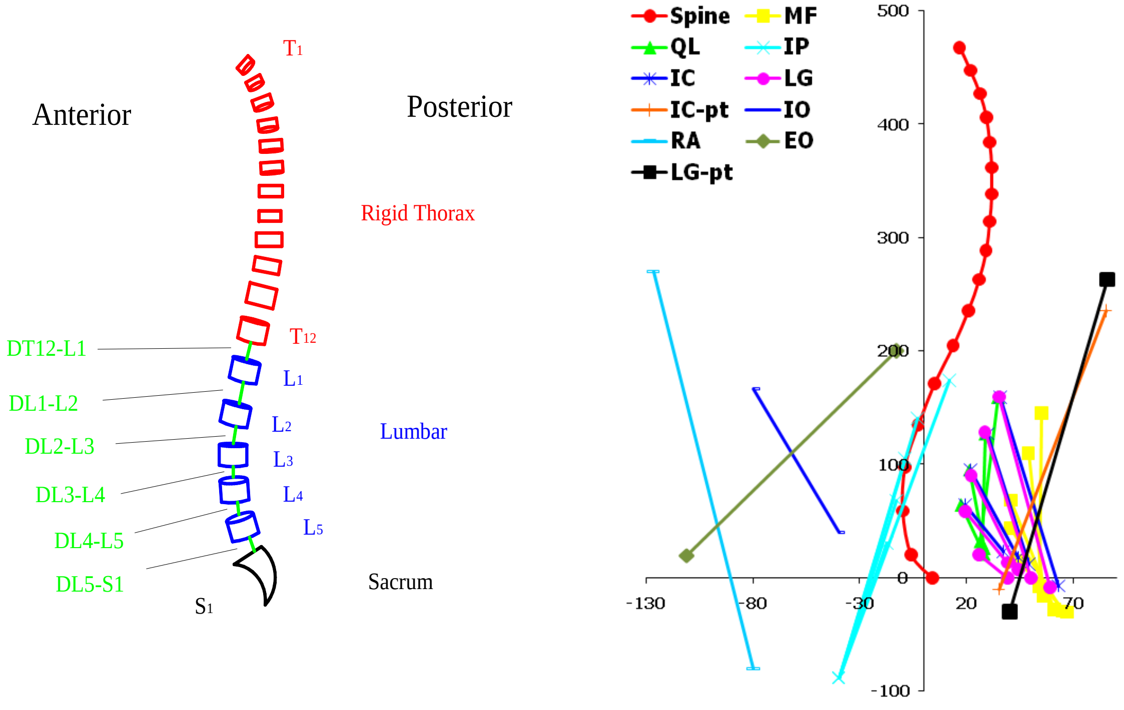

Figure 1. Sagittal view of the biomechanical model including FE model of the spine and 56 trunk muscles (dimensions in mm). ICPL: iliocostalislumborum pars lumborum, ICPT: iliocostalislumbroum pars thoracis, IP: iliopsoas, LGPL: longissimusthoracis pars lumborum, LGPT: longissimusthoracis pars thoracis, MF: multifidus, QL: quadratuslumborum, IO: internal oblique, EO: external oblique and RA: rectus abdominus.

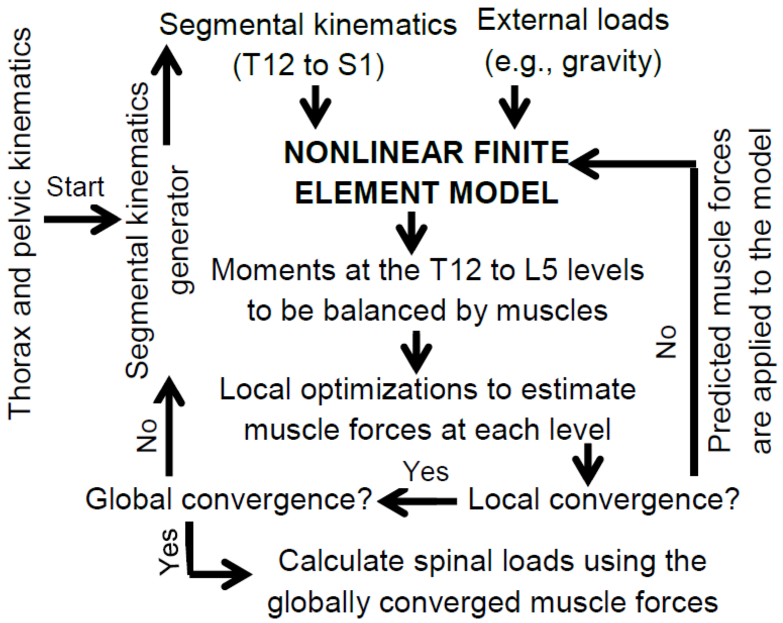

Figure 2. The process used to estimate muscle forces and spinal loads. Each set of possible segmental kinematics is generated using a genetic algorithm subjected to measured kinematics of thorax and pelvis as well as the reported values of lumbar segments' range of motion. The convergence in the local and global loops are achieved when the changes in respectively sum of predicted muscle forces in two consecutive local iterations and the value of the cost function of the heuristic optimization procedure in two consecutive global iterations are less than 1%.

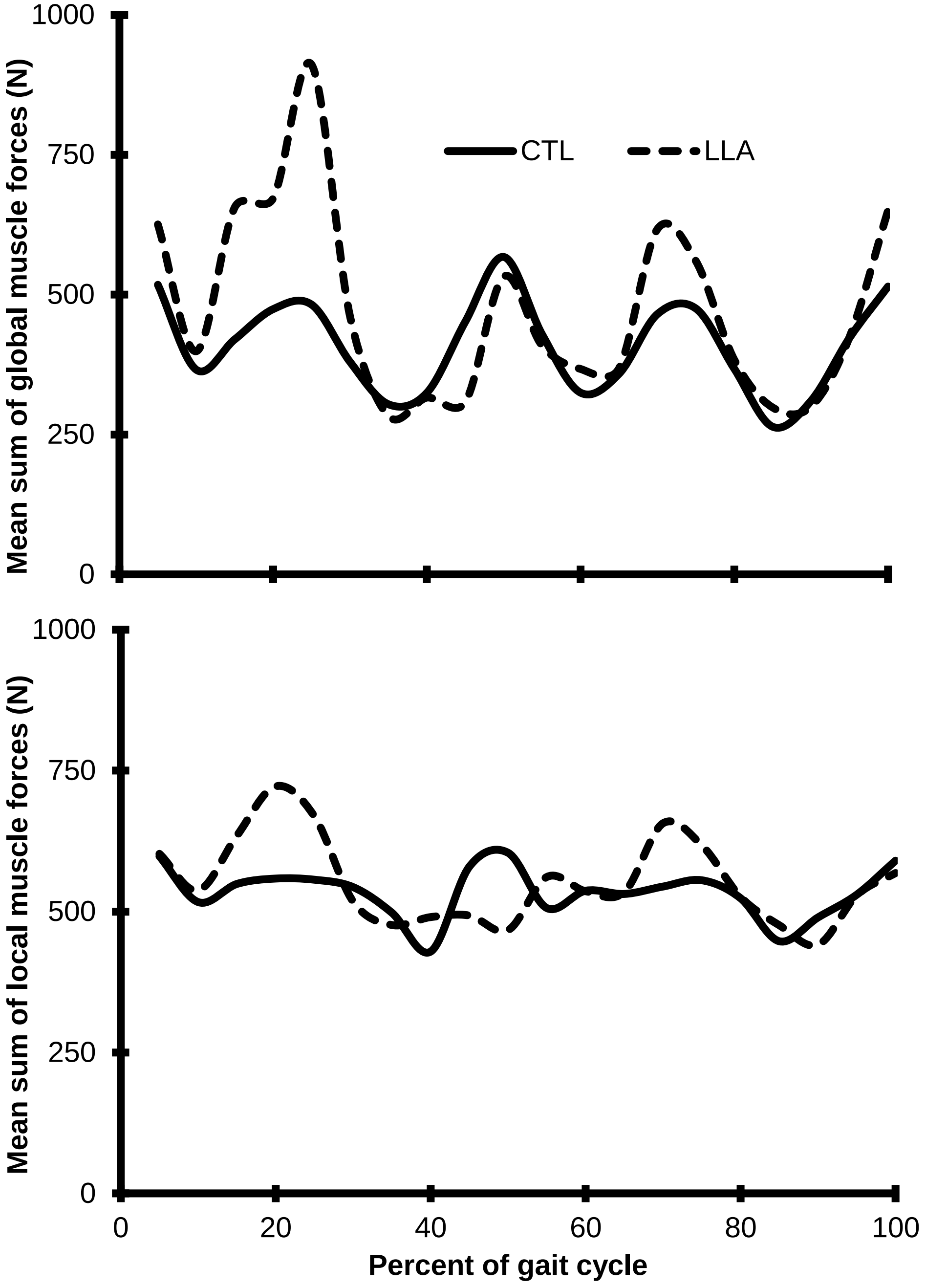

Figure 3. Mean sum of forces in global (i.e., muscles attached to the thoracic spine – top) and local (i.e., muscles attached to the lumbar spine – bottom) muscles. CTL: control group, LLA: group with lower limb amputation.

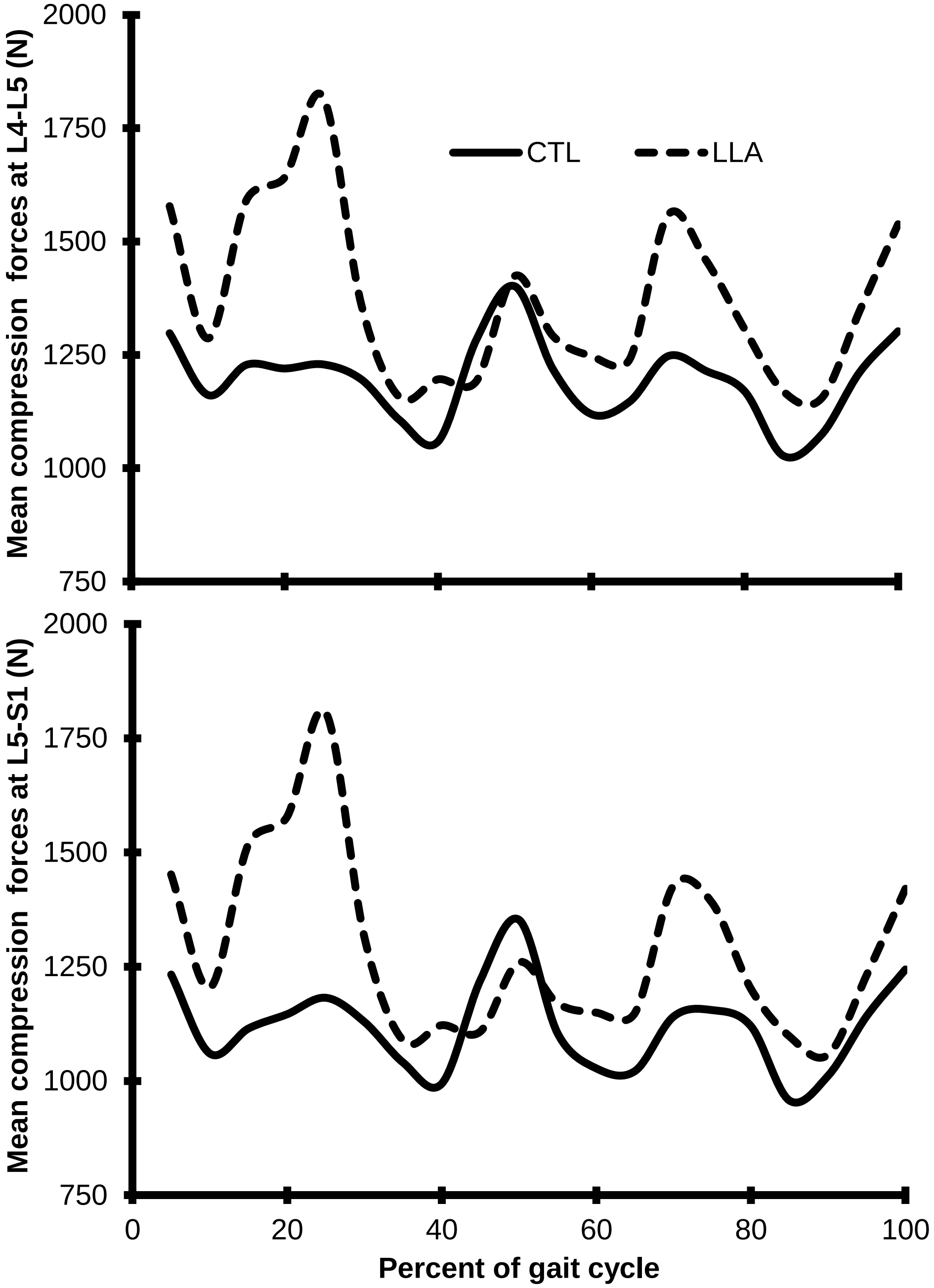

Figure 4. Mean compression forces at mid-plane of the L4-L5 (top) and L5-S1 (bottom) intervertebral discs. CTL: control group, LLA: group with lower limb amputation.

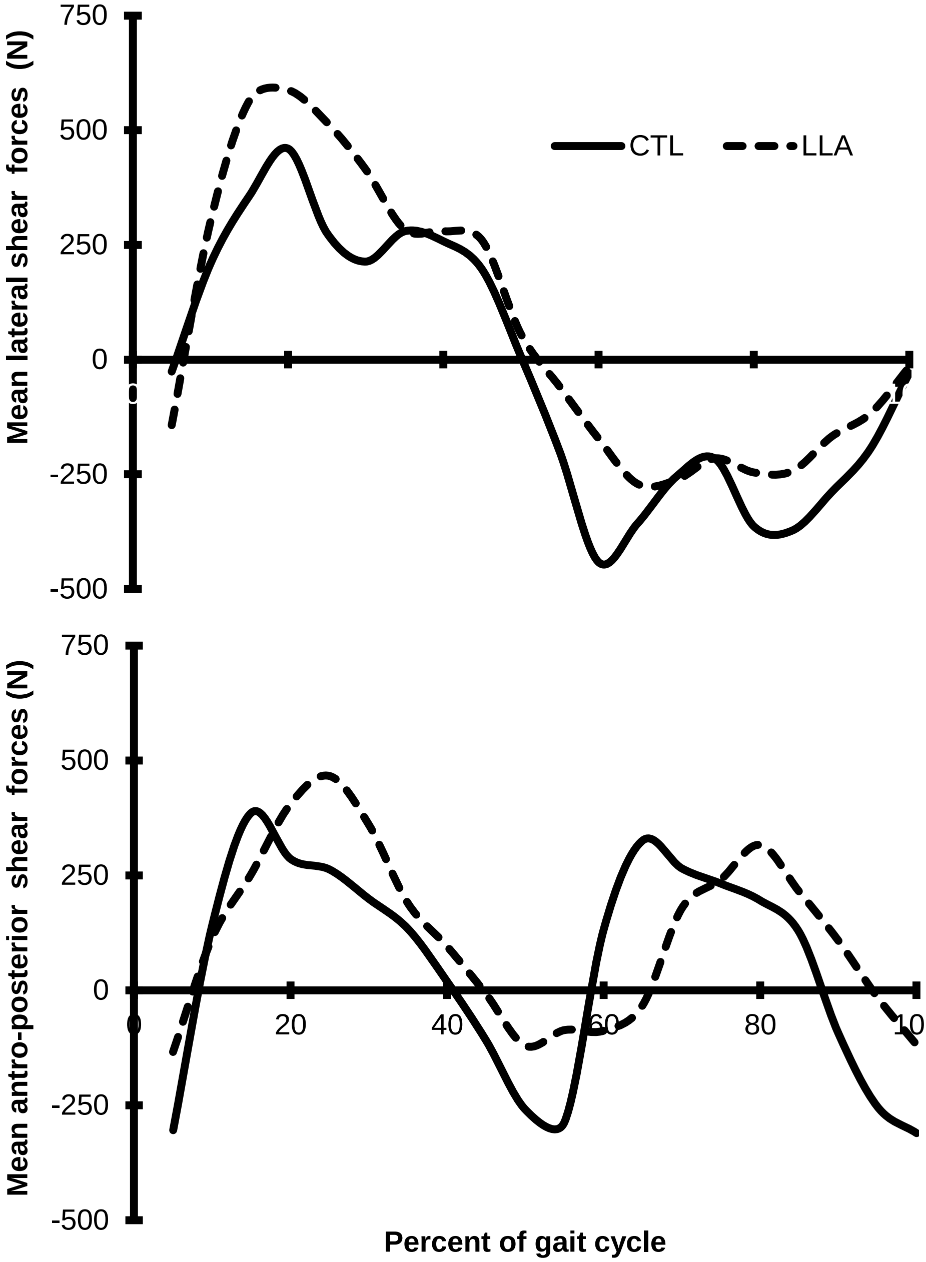

Figure 5. Mean shear forces at the mid-plane of the L5-S1 intervertebral disc in lateral (top) and antero-posterior (bottom) directions. CTL: control group, LLA: group with lower limb amputation. Positive shear force in lateral direction indicates force toward the right (intact) leg for controls (LLA) and positive shear force in antero-posterior direction indicate anterior direction.

Low Back Pain in Service Members with Traumatic Extremity Injuries: Implications of Biomechanical Risk Factors

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BACKGROUND: Low back pain (LBP) is far-reaching within the military and general population. While LBP generally has a multifactorial etiology and complex pathogenesis, biomechanical risk factors likely contribute more substantially among persons with traumatic extremity injuries, including lower-limb amputation (LLA). Specifically, persons with unilateral LLA walk and perform other activities of daily living in ways that often disproportionately rely on the intact (vs. prosthetic) limb. Such a compensational strategy is most notably associated with increased and/or asymmetric trunk movements as compared to able-bodied individuals; these movements are of particular concern given the biomechanical association between joint motions and musculoskeletal loads [1], and perceived by individuals with LLA as primary contributors toward LBP [2].

METHODS: Kinematic and kinetic data from 40 males with unilateral transtibial (n=20) and transfemoral (n=20) amputation, and 20 uninjured males, were obtained during level-ground walking at a self-selected pace. Net external demands (inverse dynamics) and bone-bone joint contact loads (finite element modeling) at L5-S1 are summarized in an effort to better understand relationships between altered trunk/pelvic motions with LLA on musculoskeletal loads within the lower back.

RESULTS: The coordination / motions between the trunk and pelvis with vs. without LLA are associated with ~31-55, 41-83, and 3-14% larger external demands on the lower back in the sagittal, coronal, and transverse planes, respectively. Similarly, joint contact forces within the spine are increased with LLA; notably, largest increases (up to ~65% relative to uninjured individuals) were found in joint compressive forces owing to a complex pattern and increased (6-80%) activation of trunk muscles. Also of note, increases were generally larger among individuals with more proximal amputations (transfemoral vs. transtibial), consistent with changes in trunk motions.

CONCLUSION: Though walking is generally not a mechanically demanding task for the low back (i.e., loads are well below reported injury thresholds), and sometimes even considered therapeutic for individuals with LBP, altered trunk-pelvic motions with LLA during gait are associated with larger external demands on the lower back and internal loads among tissues within the spine. Given the repetitive nature of gait, over time, even minimal increases in trunk motions and musculoskeletal loads may synergistically and progressively contribute toward LBP onset/recurrence and accelerate degenerative joint changes. However, to comprehensively characterize relative and accumulated risk profiles, additional efforts are needed to classify such relationships during other activities of daily living. In doing so, future work can begin to assess the ability of specific interventions (e.g., prosthetic devices, physical therapy) to mitigate injury risk.

1. Davis and Marras (2000) *Clinical Biomechanics*
2. Devan et al. (2015) *Disability and Rehabilitation*

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LEARNING OBJECTIVES:

1. Describe risk factors for low back pain with traumatic extremity injuries.
2. Define the impact of altered mechanics on the lower back and influence on low back pain risk.
3. Describe potential ways in which the elevated risk can be minimized, either clinically or with novel technologies.

review-article

COMPREHENSIVE INVITED REVIEW

Impact of Traumatic Lower Extremity Injuries Beyond Acute Care: Movement-Based Considerations for Resultant Longer Term Secondary Health Conditions

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Significance: Advances in field-based trauma care, surgical techniques, and protective equipment have collectively facilitated the survival of a historically large number of service members (SMs) following combat trauma, although many sustained significant composite tissue injuries to the extremities, including limb loss (LL) and limb salvage (LS). Beyond the acute surgical and rehabilitative efforts that focus primarily on wound care and restoring mobility, traumatic LL and LS are associated with several debilitating longer term secondary health conditions (*e.g.*, low back pain [LBP], osteoarthritis [OA], and cardiovascular disease [CVD]) that can adversely impact physical function and quality of life.

Recent Advances: Despite recent advancements in prosthetic and orthotic devices, altered movement and mechanical loading patterns have been identified among persons with LL and salvage, which are purported risk factors for the development of longer term secondary musculoskeletal conditions and may limit functional outcomes and/or concomitantly impact cardiovascular health.

Critical Issues: The increased prevalence of and risk for LBP, OA, and CVD among the relatively young cohort of SMs with LL and LS significantly impact physiological and psychological well-being, particularly over the next several decades of their lives.

Future Directions: Longitudinal studies are needed to characterize the onset, progression, and recurrence of health conditions secondary to LL and salvage. While not a focus of the current review, detailed characterization of physiological biomarkers throughout the rehabilitation process may provide additional insight into the current understanding of disease processes of the musculoskeletal and cardiovascular systems.

Keywords: amputation, biomechanics, cardiovascular disease, limb salvage, low back pain, osteoarthritis

SCOPE AND SIGNIFICANCE

Extremity trauma, including limb loss (LL) and limb salvage (LS), is commonly associated with an elevated risk for secondary health conditions (*e.g.*, low back pain [LBP], osteoarthritis [OA], cardiovascular disease [CVD]) that can significantly limit physical function, reduce quality of life (QoL), and life expectancy. This review

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provides an extensive commentary regarding resultant secondary health effects of extremity trauma in service members (SMs), with a particular focus on functional outcomes and quality of movement.

TRANSLATIONAL RELEVANCE

Physiologic biomarkers provide an opportunity to enhance translation in future work to examine the pathophysiology of the secondary health conditions associated with traumatic LL from a basic science perspective. While this approach is yet to be fully explored and thus was not a primary focus of this review, such biomarkers may augment traditional analyses and support more comprehensive risk characterization, thereby allowing clinicians and researchers to better mitigate disease onset or progression.

CLINICAL RELEVANCE

The increased prevalence of secondary health effects following traumatic extremity injuries places a significant physical and psychosocial burden on SMs with LL and LS. Altered movement patterns often result in mechanical loading of the spine and lower extremities, potentially increasing the risk of LBP and OA. Adopting a biopsychosocial model of treatment/care may allow clinicians to utilize a multifaceted approach to treat chronic pain and dysfunction associated with resultant health effects of LL.

BACKGROUND

Musculoskeletal disorders are the most prevalent source of disability in the United States.[1,2] As a result, the annual direct costs associated with treatment total a substantial $900 billion.[3] Among these, extremity amputation, or LL, is projected to affect an estimated 3.6 million people by the year 2050.[4] Approximately 185,000 individuals undergo either an upper or lower extremity amputation annually, primarily due to trauma, dysvascular disease, and/or osteosarcoma.[5–7] While the incidence of LL due to dysvascular etiologies has steadily risen among the civilian sector, trauma remains a leading source of LL within the Military Health System. However, prior estimates of the current/future impact of LL do not include SMs injured during combat nor do they consider individuals with LS; an alternative to amputation in which heroic measures are undertaken by the military surgical teams at all echelons of care to preserve as much form and function of the traumatically injured limb as possible. Despite these surgical efforts and advances in orthotic technology, many with LS are unable to achieve preinjury functional outcomes, much like those with LL.

The combat theaters of Operations: Enduring Freedom (OEF), Iraqi Freedom (OIF), New Dawn, Inherent Resolve, and Freedom's Sentinel were characterized by high-energy munitions and explosives. With advances in personal protective equipment, field-based trauma care, and surgical techniques, injuries sustained as a result of these often-improvised devices are now survivable at higher rates than conflicts past. However, traumatic extremity injuries, including LL and LS, remain a hallmark casualty of recent conflicts. Across all services, 52,351 military personnel have been wounded in action since 2001[8]; more than half of evacuated SMs have sustained extremity injuries and nearly a quarter of these are open fractures.[9] In addition, 1,703 SMs sustained injuries requiring major (or multiple) limb amputation (As of October 1, 2016; Data source: EACE-R). The decision to amputate a limb may be made in as few as 24 h post-trauma, during the first hospitalization as a secondary surgical intervention, or potentially years after LS (*i.e.*, delayed amputation).[10–13] Factors contributing to the decision include the extent and severity of injuries and resources available during the rehabilitation process.[14] Recent evidence suggests that SMs who undergo LS will typically experience more expansive complications than individuals who undergo amputation.[15–17] LS has been associated with significantly higher rates of rehospitalization, greater numbers of surgical procedures, and higher rates of surgical complications.[18,19]

Initial wound care and rehabilitation after LL and/or LS are critical to the recovery process. Such efforts are generally categorized by nine distinct phases, each with specific goals and objectives.[20] The complexity and interdependence between each phase elucidate the need for an efficient interdisciplinary approach within the overall rehabilitation paradigm. Despite these comprehensive and substantive efforts, persons with LL and LS are at an increased risk for acute secondary health conditions such as phantom limb pain, wounds/sores, vascular and nerve damage, infection, decreased physical function, and psychosocial issues. Furthermore, beyond these acute conditions, persons with LL and LS are also at an elevated risk for longer term complications including LBP, OA, and CVD, among others. Importantly, once the disease progression initiates, these longer term resultant conditions will plague these individuals for life, as SMs with extremity trauma are typically younger than 30 years at the time of injury and thus will continue living with their injuries for several decades.[17]

The long-term economic burden of trauma-related LL and LS is significant. Edwards *et al.* predicted the long-term (40 year) cost of trauma repair, rehabilitation, and lifelong prosthetic support of British soldiers wounded in Afghanistan to be approximately $444 million.[21] In the United States, the estimated average lifetime cost of treatment for unilateral lower LL is $342,716 and $1.4 million for Vietnam and OIF/OEF veterans, respectively.[22] However, such estimates are likely conservative, not fully accounting for costs associated with novel technology/repairs or, perhaps exponentially more economically burdensome over the longer term, for the wide range of healthcare costs associated with the treatment of secondary health conditions. The ability to evaluate, predict, and ultimately treat these resultant health conditions would not only help reduce these costs but also, and most importantly, preserve and/or improve function and QoL for those with LL and LS.

The risk for secondary health conditions is often related to physiological adaptations to trauma or pervasive surgical complications, poor biomechanics, and/or the prosthetic (orthotic) device itself. For SMs, in particular, the young age at which these injuries occur likely presents a unique challenge over the longer term and further highlights the importance for understanding resultant health conditions secondary to extremity trauma. Notably, the cumulative effects of many years of functional adaptations during gait and movement with extended prosthetic/orthotic device use in otherwise young and active SMs remain unclear.[23,24] This is an important distinction from civilian populations as a majority of civilians with LL are over the age of 50, incurred LL as a result of vascular damage/complications, are likely less active, and may present with different resultant health conditions/outcomes for less time.[25] Thus, as a preliminary step toward addressing this knowledge gap, the purpose of this review is to provide a commentary regarding resultant health conditions associated with high-energy extremity trauma, with a primary focus on biomechanical features of movement and associated functional limitations. In particular, we highlight considerations for longitudinal care aimed at maximizing QoL, for those with both LL and LS.

DISCUSSION

Low back pain

The World Health Organization describes LBP as any pain or discomfort for a variable duration in the lumbar spine region.[26] The onset of pain may occur suddenly, coincident to a singular traumatic event, or develop over time with age or as the result of repeated microtrauma from a given (or set of) activity(ies). Often, LBP is considered idiopathic, as pain may be present without pathoanatomical evidence of disease or structural abnormality. LBP costs nearly $100 billion annually in the United States, with a majority of this cost associated with lost wages and decreased productivity.[27] While cross-sectional figures indicate that chronic LBP affects up to 33% of adults in the general population, the incidence in persons with LL who report LBP secondary to trauma is nearly double (52–76%).[28–31] Along with this significantly higher prevalence, nearly 50% of persons with LL have reported LBP as “more bothersome” than either residual or phantom limb pain and as having a significant reduction in overall QoL metrics.[28,30,32] While the exact etiology of LBP within this population is unclear, there is a growing body of evidence suggesting that altered lumbopelvic mechanics during the (repetitive) gait cycle likely influences such risk.

Persons with lower LL frequently develop altered movement patterns to maintain balance and achieve forward progression in walking. Movement patterns can be influenced by the following, either individually or in combination: socket fit/prosthetic alignment, general deconditioning, leg length discrepancies, complications within the residual limb, and muscular imbalances.[33,34] More specifically, altered movement patterns during gait affect trunk and pelvis mechanics and contribute, at least in part, to the increased incidence of LBP in persons with lower LL and may be dependent on the extent of injury or ultimate level of amputation.[35–37] These alterations and asymmetries may increase loads on the lumbar spine during gait which, when considering the repetitive gait cycle, over time may thus contribute to the occurrence or recurrence of LBP. For example, persons with transfemoral LL tend to exhibit 10° of anterior pelvic tilt, which is considered to be a compensatory mechanism to assist in the ability to achieve hip extension during gait. Increased anterior pelvic tilt is associated with increased lumbar lordosis, which is linked to an increased incidence of LBP in persons with LL.[28,38] Previous work has demonstrated that increased loads on the lumbar spine are a direct source of LBP in the general population.[39,40] Mechanical loading of the passive and active structures of the spine is affected by both internal and external loads, such as forces produced by muscular activation, ligamentous tension, gravity, and inertia.[41]

These loads can be significant, as potentially small alterations in trunk (which accounts for nearly 2/3 of the body's mass) movement may increase joint reaction loading due to increased muscular contractions of the surrounding musculature.[42] The increased demand on the active structures (muscles) may lead to increased forces and joint loading on the passive structures (discs and vertebrae). The accumulation of these altered loads over time has the potential to augment degenerative joint changes in the spine.[39]

Similar to uninjured individuals with LBP, persons with transfemoral LL exhibit irregular trunk–pelvis coordination and movement variability.[43] Specifically, persons with LL tend to walk with a large lateral trunk lean toward the affected side; a possible neuromuscular strategy/compensation to assist in forward progression during gait.[41] This frontal plane motion has been reported to increase peak joint reaction forces and moments asymmetrically in the lumbar spine (L5-S1 integration specifically) in this population. A recent report suggested this observed frontal plane motion as a possible mechanistic pathway through which recurring exposure to altered trunk motion and cumulative spinal loading may contribute to LBP in persons with lower LL.[41] Persons with transfemoral LL (with current LBP) exhibit larger axial trunk rotations when compared to those without LBP, which may subsequently affect vertebral disc degeneration and potentially contribute to LBP recurrence.[44,45] Previous evidence demonstrated degenerative changes in the lumbar spine via radiographic imaging in 76% of persons with LL, potentially supporting the role of increased trunk motion leading to degenerative changes in this population.[46]

While LBP is commonly cited as a secondary health effect of LL, persons with LS may also experience LBP as a result of altered movement patterns during gait and functional activities.[47] Persons with LS typically experience reduced ankle function, which is associated with altered gait mechanics and increased metabolic cost.[34,48,49] However, the influence of distal LS on proximal (trunk/pelvis) biomechanics remains unstudied to date. Currently, a paucity of evidence exists relative to the prevalence of LBP in the LS population. Therefore, further work is needed to elucidate the relationship between LS and the development of LBP.

In summary, LBP has been reported as the most important health-related physical condition contributing to a reduced QoL among veterans who had sustained a traumatic lower extremity amputation over 20 years prior.[32] Thus, identifying factors contributing to the development and recurrence of LBP, such as a widely prevalent and "bothersome" secondary health concern, is critical for improving long-term health. Abnormal mechanical loading of lumbar spine, altered trunk and pelvis coordination, and psychosocial factors may influence the prevalence of LBP in this population. Therapeutic interventions that address the underlying impairment(s) in trunk neuromuscular responses and/or motor control strategy may also contribute to reducing the prevalence and incidence of LBP among SMs with lower extremity trauma, thereby improving longer term functional outcomes by mitigating a significant secondary impairment with a substantial adverse impact on daily activities. Further evidence is needed to understand the relationship between these risk factors and the incidence of LBP in persons with LL. In particular, no studies to date have evaluated the influence of different prostheses or orthoses on the incidence of LBP in the traumatic LL and LS populations.

Osteoarthritis

The National Institute of Arthritis and Musculoskeletal and Skin Diseases describes OA as a joint disease affecting the cartilage, often characterized by pain and stiffness within a joint and limitations in physical function.[50] The primary pathology is articular cartilage deterioration, although evidence suggests that possible morphological changes of bone are reflective of disease onset. Within the joint, articular cartilage functions to dissipate forces sustained by the bony structures throughout motion. During activities such as walking or running, when the loading velocity and intensity of the structures are increased, the cartilage's ability to dissipate forces is reduced.[51] In the general population, mechanical loading of the knee joint during walking has been associated with the presence, severity, and progression of knee OA.[52–55] Persons with unilateral lower LL are 17 times more likely to suffer from knee OA in the intact limb when compared to able-bodied individuals.[56]

As previously noted, persons with LL frequently develop altered movement patterns during gait. Of particular importance here, those with unilateral LL preferentially utilize their intact limb, leading to increased and prolonged loading of the intact joints. Mechanical alterations in static and dynamic alignment of the knee joint may affect joint loading as increased forces are incurred through medial or lateral aspects of the joint. The external knee adduction moment (EKAM) is a vastly reported risk factor for knee OA based on its relationship with internal loading of the medial joint surface.[57] The size of the EKAM and its respective angular impulse are associated with knee OA severity and progression.[52,54,58,59] During gait, individuals with lower LL asymmetrically load their intact limb to a greater extent than their involved limb, suggesting that mechanical factors play a role in the increased incidence of knee OA in this population.[36,60] For example, Lloyd *et al.* identified larger peak knee adduction moments in the intact relative to involved limb.[61] This increased mechanical loading may be explained by decreased push-off power and ground reaction forces demonstrated with conventional prosthetic feet.[60,62] Push-off power generated by the prosthetic foot instance may affect the ground reaction forces at heel strike in the intact limb as the velocity of an individual's center of mass changes from an anterior and inferior direction to an anterior and superior direction during gait.[63] The redirection of the center of mass is caused by the ground reaction impulse through the gait cycle, crudely relative to double-limb support.[63] If the prosthetic stance foot lacks adequate push-off power to propel the center of mass anteriorly, the intact limb must compensate by performing more work to move the center of mass anterior and superior, resulting in increased ground reaction forces and loading of the intact limb.[60] Morgenroth *et al.* suggested that by utilizing a prosthetic foot with increased push-off power, the peak EKAM of the intact limb may be reduced and therefore potentially decreasing the OA risk.[60] This was supported as a powered ankle–foot prosthetic was able to decrease the EKAM and vertical ground reaction force in persons with lower LL, however, the prosthetic used was unable to alter the knee joint loads of the intact limb.[64] Similar to LBP, the progression and severity of OA may be further amplified by psychosocial determinants; anxiety, depression, coping strategies, and stress have also been associated with increased pain in patients with OA.[65–67]

OA is not exclusive to the LL population as individuals with LS present with similar (sometimes larger) gait and movement deviations. As high as 95% of OA diagnoses among combat-wounded SMs are post-traumatic in origin.[68] Chronic pain, nerve damage, and volumetric muscle loss are common barriers to LS rehabilitation and may serve as confounding factors in the development of OA treatment plans.[69,70] Ankle–foot orthoses (AFOs) are commonly used to assist ankle function or offload painful structures.[71] Optional therapies that include sports medicine-based interventions utilizing a dynamic AFO (*e.g.*, the Intrepid Dynamic Exoskeletal Orthosis) are available to LS patients. Such devices are designed to improve functional performance on tasks such as walking, changing directions, sit-to-stand, and ascending stairs.[47] While dynamic AFOs are suggested to improve functional capabilities, evidence is inconclusive in its ability to positively alter gait parameters related to OA as well as the effects of long-term use.[34,72,73]

Treatment modalities focused on reducing symptoms and OA disease progression in persons with LL and LS are vital to improving QoL. The Osteoarthritis Research Society International recommends biomechanical interventions, intra-articular corticosteroids, exercise (land and water based), self-management and education, strength training, and weight management.[74] Autologous platelet-rich plasma (PRP) therapy is a therapeutic intervention that delivers high concentrations of growth factors to an area to stimulate healing.[75] Recent evidence suggests that PRP may provide relief of knee OA symptoms in younger patients within the early stages of cartilage degeneration.[76–78] Strength training (weight and body-weight training) and exercises such as t'ai chi have demonstrated the ability to improve overall function in decreasing pain in OA patients and may also serve to assist in weight management.[79,80] Weight reduction is considered a pragmatic therapy for knee OA as overweight individuals demonstrate a high prevalence of knee OA and the risk of severity progression increases 35% for every 5 kg of weight gain.[81] Strength training and weight management are considered integral aspects of the rehabilitation paradigm for persons with LL as deficits in strength and increases in weight influence gait, joint loading, movement efficiency, and cardiovascular health. Canes, knee braces, and foot orthotics are other potential treatment options to decrease movements at the knee, reduce pain, and improve function.[82–84]

In summary, biomechanical factors likely play a substantial role in the risk for OA secondary to extremity trauma, whether LL or LS. While the prevalence of OA in LL and LS populations may decrease as technological improvements in prostheses and orthoses are realized, further evidence is needed to determine the specific relationship between different classes or features of these devices and OA risk factors. Unfortunately, recent technological advancements in prosthetic devices have outpaced orthotic devices, the benefits of which are evident in the biomechanical characteristics of persons with LL versus LS. Nevertheless, LS typically presents with more complex neurovascular injuries and other unique challenges, which can negatively affect functional outcomes.

Cardiovascular disease

CVD is defined by a vast array of diseases affecting the heart and blood vessels.[85] CVD may present as coronary artery disease, stroke, arrhythmias, cardiomyopathy, heart disease, peripheral artery disease, aneurysms, venous thrombosis, and/or carditis.[85,86] While CVD is largely preventable, it remains the leading cause of death worldwide, particularly in lower socioeconomic demographics.[85] The American Heart Association reports there are ~85 million individuals with CVD in the United States, causing a staggering 2,200 deaths each and every day.[87] This is accompanied by direct and indirect costs of nearly $315 billion.[88] Risk factors for CVD include, but are not limited to, family history and genetics, high cholesterol and lipids, high blood pressure, diabetes, metabolic syndrome, obesity, and kidney disease.[88] In addition, significant combat trauma may be a risk factor for the development of CVD.[89–91] For example, Hrubec and Ryder conducted a 30-year follow-up of World War II veterans with lower LL and demonstrated that the relative risk of CVD mortality was increased 2.4–4 times that of persons with LS.[89] Similarly, Modan *et al.* reported significantly higher mortality rates of persons with traumatic lower LL when compared to able-bodied controls, suggesting that CVD was the primary cause (21.9% vs. 12.1%, $p < 0.001$).[90]

The pathophysiology of increased mortality rates may be a result of systemic and/or regional hemodynamic effects of trauma.[90,92–96] Obesity and hypertension secondary to decreased overall activity levels may lead to insulin regulation complications in persons with LL.[96] When compared to uninjured controls with no difference in body mass index, blood pressure, or lipid levels, persons with LL exhibited significantly higher increased fasting plasma insulin levels as well as insulin resistance.[95] Increased plasma insulin levels and insulin resistance are risk factors for atherosclerosis and metabolic syndrome, considered precursors to CVD. The role of psychological stressors in the development of CVD is not well understood; however, psychosocial factors have demonstrated involvement in the pathogenesis of CVD.[97,98] Depression and post-traumatic stress disorder have been associated with increased incidence of CVD, while veterans with high levels of cynical distrust and anger demonstrate an accelerated progression of atherosclerosis, a risk factor for CVD.[99–101] Limited evidence precludes a definitive relationship between psychosocial factors and CVD risk in persons with LL, and therefore, future work should prospectively examine the relationship between psychosocial factors/stressors and the development of CVD.

Hemodynamically, proximal amputation increases the risk of CVD development based on alterations in proximal arterial flow. Pathogenic mechanisms may include early reflection pulse waves. Early return reflection pulse waves are produced at arterial occlusion sites and have been linked to a myriad of medical complications.[102] An early returned reflection pulse wave creates a second systolic peak, which results in an increase in aortic pressure. The increased aortic pressure generates an increased left ventricular load resulting in left ventricular hypertrophy, atherothrombosis, and ultimately cardiac death.[103] Vollmar *et al.* suggested that persons with traumatic LL above the knee were five times more likely to suffer from abdominal aortic aneurysms when compared to healthy controls.[93] A possible explanation may be that after amputation, blood flow is decreased by ~25% in the terminal aorta due to altered flow paths in the visceral and renal arteries, resulting in a disrupted flow pattern at the aortic bifurcation.[94] Altered flow patterns, paired with increased shear stress along the convex aspect of the aorta and decreased shear stress along the concave aspect, are theorized to damage aorto-iliac blood vessels by increasing hydraulic forces within the aorta.[94] Persons with transfemoral LL should have regular consultations with appropriate medical personnel to assess the risk of abdominal aortic aneurysm.[94]

While the hemodynamic effects of trauma appear to influence CVD risk, addressing modifiable risk factors may be an effective strategy to help decrease CVD risk. It is widely accepted that habitual exercise with activities such as running, walking, bicycling, rowing, and swimming increases aerobic capacity and decreases the risk of CVD. When joined with dietary modifications, regular exercise can effectively reduce excess body weight, another risk factor for CVD. Moreover, the increased risk of CVD in persons with LL highlights the importance of managing modifiable risk factors, engaging in preventative treatment strategies, and adopting an active lifestyle.

SUMMARY

Maintaining an active lifestyle is critically important for physiological health, psychological well-being, and overall QoL. Such guidance is no different for individuals with LL and LS. However, given the limited (but growing) body of evidence relating movement abnormalities to altered musculoskeletal demands that may lead to the development of longer term secondary conditions in this population, additional consideration for the quality of movement during recreational and daily activities is warranted. While the overwhelming focus of recent efforts has been on persons with LL, the aforementioned secondary health conditions are likely also major concerns for those with LS. As such, we posit that an underlying focus of clinical care and future research, in both cohorts, should be toward mitigating concomitant risk for the development or recurrence of chronic pain.

While advances in trauma care and prosthetic/orthotic technologies may eventually mollify acute and subacute secondary health effects of extremity trauma, longitudinal tracking is urgently needed to better understand the mechanisms by which secondary health effects develop
AU4 ▶ and progress in this population. Such efforts should encompass a transdisciplinary team, in which a comprehensive suite of evaluation metrics—for example, traditional clinical evaluation and movement analysis supplemented with local and/or system physiological biomarker analysis, and next-generation imaging modalities, among others, will facilitate a deeper understanding into the development and progression of secondary health effects of LL and LS. In doing so, a better understanding of the specific pathways for the development of these secondary health effects can be realized, thus enabling clinicians to develop and prescribe appropriate treatment interventions. Ultimately, diminishing risk factors relative to the degeneration of joint and cardiovascular function will reduce the overall prevalence of secondary health conditions and improve QoL for our nation's injured SMs and veterans over the longer term.

TAKE HOME MESSAGES

- Living with LL over time leads to increased morbidity and mortality from secondary medical and musculoskeletal problems. Awareness of the long-term health risks associated with LL, as well as the physiologic and biomechanical origin of these risks, is critical to improving outcomes
- Understanding the pathogenesis of the secondary health conditions of traumatic LL and salvage may help guide optimal management in acute, subacute, and chronic phases of care for these individuals
- Reducing modifiable risk factors through patient education, identifying appropriate support systems, encouraging proper gait mechanics, and utilizing the prescription of evolving technologies may help mitigate long-term health conditions

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Abbreviations and Acronyms

AFO = ankle–foot orthoses
CVD = cardiovascular disease
EACE = Extremity Trauma and Amputation Center of Excellence
EKAM = external knee adduction moment
LBP = low back pain
LL = limb loss
LS = limb salvage
OA = osteoarthritis
OEF = Operation Enduring Freedom
OIF = Operation Iraqi Freedom
PRP = platelet-rich plasma
QoL = quality of life
SM = service member
USUHS = Uniformed Services University of the Health Sciences
WRNMMC = Walter Reed National Military Medical Center

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FASTER WALKING SPEEDS DIFFERENTIALLY ALTER SPINAL LOADS IN PERSONS WITH TRAUMATIC LOWER LIMB AMPUTATION

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Persons with lower limb amputation (LLA) commonly report low back pain and perceive altered trunk motions/postures during activities of daily living as primary contributors [1]. When walking at a self-selected pace, our prior work has demonstrated altered trunk motions among persons with vs. without LLA are associated with 26-60% increases in spinal loads [2]. Here, we expand these efforts by presenting preliminary data of a much larger sample[a] regarding the influence of walking speed on spinal loads in this population. Trunk and pelvic kinematics, collected during level-ground walking at 3 controlled speeds (~1.0, 1.3, and 1.6 m/s), were extracted for 1 male servicemember with unilateral transfemoral amputation (35 yr, 173.0 cm, 106.8 kg) and 1 male servicemember without amputation (27 yr, 179.0 cm, 72.0 kg). These kinematic data were input to a kinematics-driven, non-linear finite element model of the lower back to estimate the resultant compressive and lateral/anteroposterior shear loads at L5/S1 using an optimization-based iterative procedure [3]. Peak compressive, lateral, and anteroposterior shear loads generally increased with increasing walking speed. However, increases in compression and lateral shear with increasing walking speed were larger among the person with vs. without LLA, particularly in lateral shear at the fastest speed (Figure 1A-B). In contrast, peak anteroposterior shear decreased with increasing walking speed among the person with LLA (Figure 1C). Although walking is generally not a mechanically demanding task for the low back (i.e., loads are well below reported injury thresholds), walking faster for persons with LLA appear to differentially alter external demands on the lower back and internal loads among tissues within the spine. Thus, over time, repeated exposures to faster walking speeds may contribute to the elevated risk for low back pain after LLA, due to fatigue failure of spinal tissues, though further work to more completely characterize spinal loads during activities of daily living is warranted.

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[a] Final results from n ≥ 20 in each group (with additional speeds and levels of amputation) will be presented at the workshop

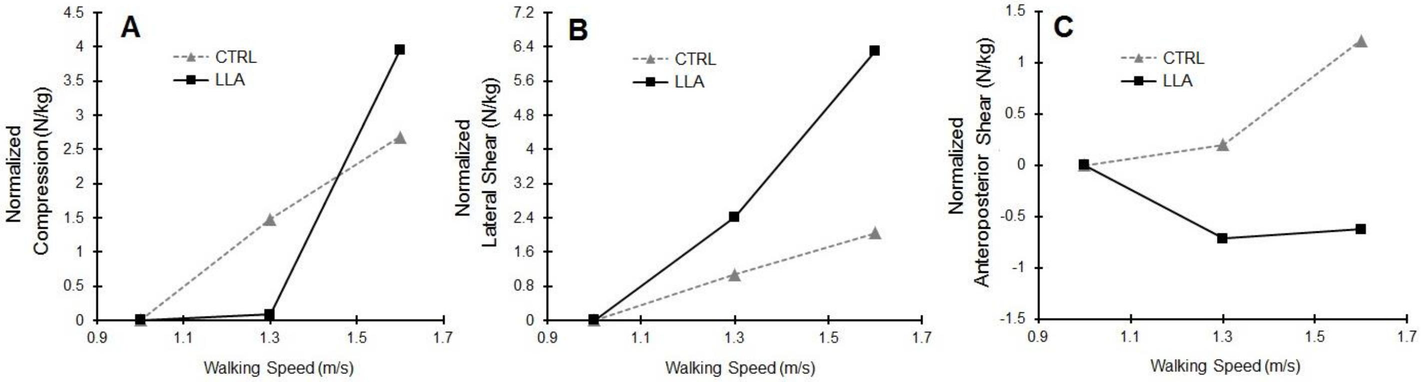

Figure 1. Normalized changes in (A) compression, (B) lateral shear, and (C) anteroposterior shear with increasing walking speed, for an individual with lower limb amputation (LLA) and an uninjured control (CTRL). To highlight the influences of walking speed, changes in spinal loads are shown with respect to values obtained in the 1.0 m/s walking speed and are normalized by body mass.

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The Biopsychosocial Correlates of Chronic Low Back Pain after Lower Limb Amputation

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ABSTRACT

Low back pain is a common secondary health condition after lower limb amputation with important implications related to functional capabilities and overall quality of life. Despite the high prevalence of low back pain after lower limb amputation, the underlying etiologies of the disorder remain unknown. This special communication summarizes evidence in support of the multifactorial, biopsychosocial model of the low back pain experience in the general population and after lower limb amputation for identification of potential risk factors and treatment targets. Key findings that link biological, psychological, and social factors and the experience of low back pain after lower limb amputation are discussed while highlighting gaps in our current state of knowledge to direct future research. Importantly, the aim of this special communication was not to propose a new model, but rather to organize data originating from prior work into a coherent conceptual framework to better understand the need for multifaceted and multidisciplinary intervention approaches for effective treatment of low back pain after lower limb amputation.

INTRODUCTION

Low back pain (LBP) is a common health condition worldwide, with 11-38% of the general population reporting symptoms over a one year period.[1, 2] LBP is currently considered the leading cause of disability globally, ahead of 290 other conditions, and is responsible for 83 million years lived with disability.[3] Additionally, LBP is a major source of activity limitation, work absenteeism, and increased cost of medical care throughout much of the world.[2, 4-6] LBP is also a common and perhaps more impactful, secondary health condition after lower limb amputation (LLA), with high estimated annual prevalence rates between 50-90%.[7-13] Individuals with LLA often report more LBP after amputation than before[8, 9] and in most cases directly attribute their LBP to their amputation.[10] Additionally, presence of LBP daily or several times per week has been associated with moderate to severe physical disability and limitations in performing daily activities in patients with LLA.[8, 9, 13-15] To this end, LBP is often rated by patients with LLA as more bothersome than phantom or residual limb pain,[11] suggesting LBP is an important secondary musculoskeletal condition associated with functional limitation and disability after LLA.

Despite the high prevalence of LBP after LLA, the exact etiologies of the disorder in this population remain unknown, thereby making its treatment exceptionally challenging. Importantly, there are currently no published guidelines specifically tailored toward the management of LBP for individuals with LLA. Therefore, there exists a clear need for comprehensive identification of contributing factors to the LBP experience after LLA that can serve as a basis for the development of targeted treatments and future research investigations. Here a new application of the multifactorial, biopsychosocial model for LBP, previously developed for the general population,[16-18] is proposed as a way of identifying risk factors and potential treatment targets for treatment of LBP after LLA. The objective of this special communication was to organize data originating from prior studies of the biopsychosocial correlates of LBP after LLA into a coherent conceptual framework. We hypothesized that alterations in biological, psychological, and social factors with LLA are related to the development of LBP symptoms and disability after LLA that merit specific attention during the clinical decision making process and for future research efforts to improve patient-related outcomes.

The Biopsychosocial Model of Low Back Pain

Treatment of LBP has historically centered around the traditional biomedical model of illness, which assumes a direct relationship between regional pathoanatomy and the perception of pain.[18] As such, it was expected that once the anatomical source of LBP is identified, biochemical and/or mechanical treatments of underlying pathoanatomy would result in cessation of pain. Despite leading to successful treatment of many other disease processes, the outcomes of interventions based on the biomedical model have proven to be less than ideal for treatment of LBP.[18-20] One potential reason for the failure of the biomedical model to provide an effective treatment option for LBP is that no single underlying pathoanatomical lesion has been consistently identified,[18] with up to 85% of LBP patients left without a precise pathoanatomical diagnosis.[21] Additionally, determination of pathoanatomical sources of LBP frequently lacks interexaminer reliability and evidence for generalizability.[22] The often equivocal outcomes from many “lesion-specific” treatment options such as intra-articular corticosteroid injections[19] and spinal fusion surgeries,[20] along with the generally poor predictive value of diagnostic imaging for identification of pathoanatomical pain sources,[23] have led to a recent paradigm shift toward a “non-structural” approach for the management of LBP.[24]

A growing body of evidence now suggests that successful treatment of LBP should include biological, psychological, and social assessments to comprehensively address the patient's unique pain experience.[18] The so called "biopsychosocial model" of LBP suggests that the patient's perceptions and reactions to pain should also be considered as these factors often lead to unnecessary avoidance of physical activity and social interactions, work absenteeism, and high health care utilization.[16, 17] Whereas the pathoanatomy may initiate the pain process, the psychological and social factors appear to play an important role in exacerbating the biological component of LBP by influencing the perception of pain.[25] For example, it has been hypothesized that the presence of mechanical LBP can lead to a pain-generated stress response that could have a negative impact on the endocrine and immune systems, which in turn may negatively affect the cognitive assessment, emotional response, coping strategies and health practices of the individual.[26]

Proponents of the biopsychosocial model argue that the complex, multidimensional nature of LBP does not lend itself to the reductionist view of the biomedical model; instead, the patient's unique biologic, psychological, and social factors must equally be considered.[18] Therefore, the term biopsychosocial implies that the biological, psychological and social factors are interwoven within the context of the patient's overall LBP experience and should be directly and concurrently considered as a part of a comprehensive treatment program.[26] In support of this theory, multidisciplinary treatment approaches that include biopsychosocial components for treatment of LBP in adults have demonstrated positive effects on pain, disability, and health-related quality of life.[27, 28] It stands to reason that LLA likely amplifies and/or alters specific components within the multifactorial biopsychosocial model of LBP**,** previously suggested for the general population. Given that LLA may differentially affect the various components of this model **(Figure 1)**, discrimination of clinically meaningful sub-groups of patients with LBP after LLA will most likely require assessments of biological, psychological and social domains,[22] which have not been previously evaluated in this patient population.

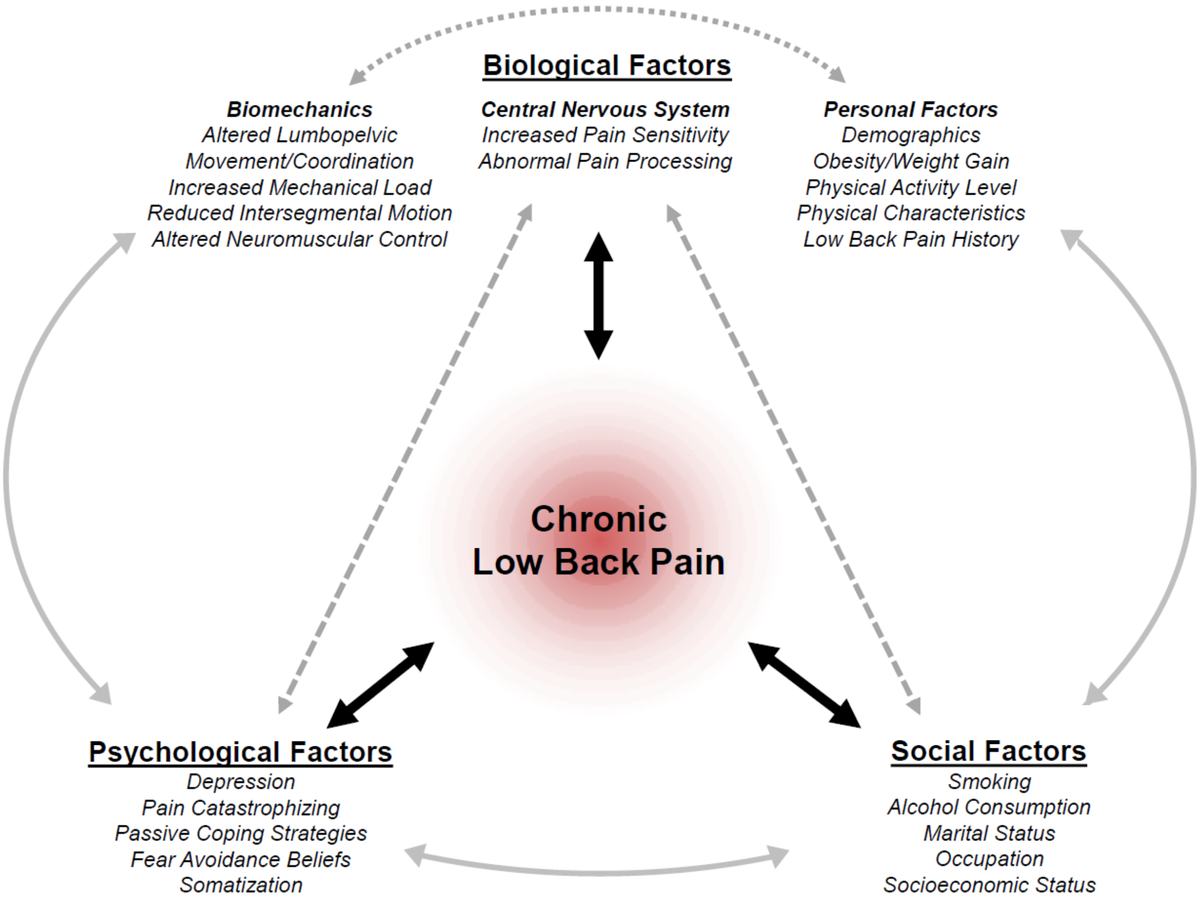

Figure 1. Individual components (and their potential associations) of the biopsychosocial model of low back pain likely influenced or amplified by lower limb amputation.

Biological Factors

Biomechanics

Altered mechanics of gait and movement have been historically proposed to play a causative role in the development and/or recurrence of LBP after LLA.[29] In fact, persons with LLA perceive “uneven postures and compensatory movements” affected by “fatigue” and "prosthesis-related factors" during functional activities as the primary contributors to LBP.[30] Though at the expense of higher metabolic cost of transport,[31] compensatory movement strategies adopted after LLA typically involve adaptations to maintain the body's center of mass within the base of support (i.e., improve stability and balance), primarily with a preference for the intact limb, if applicable.[32] During gait, for example, the intact limb (relative to prosthetic limb) is characterized by a longer stance time, shorter step length, wider stride width, and larger vertical ground reaction forces.[33] As the trunk accounts for approximately two-thirds of total body mass,[34] altered motions of this segment play a substantial role in post-amputation movement strategies, thereby warranting more trunk-focused biomechanical investigations for assessing potential links with the development and persistence of LBP.

Altered trunk and pelvic movements in persons with LLA have been previously identified in all three cardinal planes, including larger forward trunk lean and flexion-extension range of motion, greater lateral trunk flexion (towards the prosthetic limb) and pelvic obliquity motion, as well as more axial rotations between the shoulders/pelvis or regional/intervertebral motion segments.[35, 36] The presence (and likely severity) of LBP further influences such motions, most notably increasing axial rotations within the lumbar region.[37] LBP has also been associated with more in-phase mediolateral coordination between the trunk and pelvis,[38] which is indicative of inter-segmental rigidity (i.e., "guarding behavior") previously reported in able-bodied individuals who are experiencing LBP.[39, 40] Additional evidence suggests that individuals with LLA employ an active mediolateral trunk movement strategy, inferred from increases in generation and absorption of energy between the trunk and pelvis.[41, 42] Although actively increasing mediolateral trunk sway is likely an attempt to improve joint stability within the lower extremity by altering lever arms of ab/adductor musculature,[43] most notably within the hip among patients with transfemoral amputation,[7] such strategies have been associated with LBP/discomfort among able-bodied individuals performing gait training aimed at reducing knee joint loads via trunk lateral flexion.[44]

Abnormal mechanics of the spinal column, primarily larger mechanical loads and instability, are often considered risk factors for the development of LBP.[45] Of particular interest here, characteristics of trunk motion can directly influence musculoskeletal loading,[46] typically due to altered muscular response (i.e., coactivity).[45] Though walking is generally not a mechanically demanding task for the low back (i.e., loads are well below reported injury thresholds),[47] and sometimes even considered therapeutic for individuals with LBP,[48] altered trunk-pelvic motions with LLA during gait have recently been associated with large internal loads among tissues within the spine.[49-51] Notably, largest increases (up to ~65% relative to uninjured individuals) were found in joint compressive forces owing to a complex pattern of muscle responses.[50] Given the repetitive nature of gait, over time, even minimal increases in trunk motions and musculoskeletal loads may synergistically and progressively contribute toward LBP onset and/or recurrence and accelerate degenerative joint changes in the spine.

It is well accepted that the neuromuscular system plays a central role in supporting the upper body and maintaining mechanical equilibrium and stability of the spine.[52, 53] Irregular patterns of trunk muscle recruitment have been identified among the general population with recurrent LBP,[54] and impaired postural control has been associated with spinal instability and LBP.[55] Among persons with LLA without LBP, similar assessments have identified impairments in trunk postural control during an unstable seated balance task,[56] bilateral asymmetries in trunk mechanical and muscular responses to applied positional perturbations,[57] as well as altered load-sharing between active and passive trunk tissues during quasi-static trunk flexion/extension movements.[58] Additionally, substantially greater fatigability has been reported for the low-back extensor musculature in patients with LLA with and without LBP,[15] that are more pronounced than healthy individuals with and without LBP.[59] Fatigue of the low back extensors may further contribute to increased intersegmental spinal motion and instability during prolonged functional activities.[60] Though the specific origin and functional impact of such alterations remain somewhat speculative, these data support the theory that repeated exposure to altered loading associated with LLA and repeated use of a prosthetic device may result in tissue and neuromuscular adaptations and increased risk for LBP in this population.

Central Nervous System

In addition to changes in trunk/pelvic biomechanics with LLA, central nervous system factors may also play an important biological role in the manifestation of LBP after LLA. Because of the trauma to peripheral nerves, amputation has the potential to influence the processing of pain signals in the peripheral and central nervous systems. Phantom limb pain has been long described as the perception of pain in the missing (amputated) limb,[61, 62] and may be indicative of alterations in the processing of pain signals. Although it is unknown how alterations in pain processing might influence the incidence and prevalence of secondary musculoskeletal pain problems, such as LBP, there are several plausible explanations.

In the general population, people with LBP display generalized hypersensitivity to pain that is reflective of central sensitization.[63] Central sensitization is the increased neuronal responsiveness to a stimulus due to prolonged or strong activity in the dorsal horn neurons that may be associated with an episode of pain or prolonged pain.[64] It is plausible that the pain stimulus associated with amputation could elicit central sensitization and increased pain sensitivity, putting persons with amputation at risk for developing secondary pain conditions. Pain sensitivity is typically evaluated by assessing thresholds and tolerance to pain using a variety of modalities for stimuli, including: mechanical (pressure), electrical, and thermal (cold/heat).[63] Changes in pain sensitivity also can be measured after either an inhibitory stimulus (conditioned pain modulation), or a facilitory stimulus (temporal summation) to further elucidate central mechanisms of pain inhibition or facilitation. Specific alterations in pain processing that have been reported in people with LBP include local[65, 66] and widespread[65-70] hyperalgesia and enhanced temporal summation of pain signals.[71-74] Although people with chronic pain conditions such as osteoarthritis, fibromyalgia, and chronic fatigue syndrome also typically display decreased inhibition of nociceptive signals (conditioned pain modulation),[75-77] most studies report that people with chronic LBP display normal inhibition of pain signals.[78-80]

Pain sensitivity has been examined to a limited extent in persons with amputation. In a small sample, Li et al.[81] reported that persons with traumatic amputation and phantom limb pain displayed decreased thresholds for sensation and pain with electrical stimuli in the unaffected limb, suggesting central sensitization. Further, Vase et al.[82] reported that people with upper limb amputation and phantom limb pain display decreased thresholds for pressure and cold stimuli, and enhanced temporal summation of pain signals. Inhibition of nociceptive signals has not been explicitly examined in person with amputation, but it is plausible that those with phantom limb pain may display decreased inhibition of pain similar to people with other chronic pain conditions. Although the mechanisms of altered pain processing are similar in persons with amputation and people with LBP, to our knowledge, no investigators have examined the neurophysiology of pain in patients with amputation and secondary musculoskeletal pain problems to determine whether central sensitization places them at greater risk for secondary pain conditions.

Alterations in pain-processing areas of the brain in persons with amputation are also consistent with changes reported in otherwise uninjured individuals with LBP. For example, thalamic structural variations and, more specifically, decreases in gray matter of the posterolateral thalamus have been reported in people with amputation.[83] These changes appear to be positively correlated with duration of time since amputation, suggesting that they may be related to reduced afferent input.[83] Further, Lotze et al.[84] reported shifts in motor and sensory cortical activation patterns during movement in patients with phantom limb pain compared to pain-free persons with amputation, while Makin et al.[85] reported cortical reorganization of the sensorimotor cortex following arm amputation regardless of phantom limb pain. Collectively, these data suggest that neuroplastic changes associated with chronic pain in persons with amputation may involve cortical reorganization.[84] Similar alterations in brain morphology, including reduced density of gray matter in the dorsolateral prefrontal cortex, the thalamus, and the middle cingulate cortex has been reported in patients with LBP without amputation.[86] Although similar neuroplastic changes have been observed in some people with limb amputation and in people with LBP,[87] whether the similarities in mechanism might be related to the development of LBP in persons with LLA requires further investigation. Identifying the contribution of altered pain processing to LBP in patients with amputation could inform the development of more targeted and individualized interventions

Personal Factors

The link between personal demographics and LBP has been well studied in the general population. Prevalence of LBP has been reported to increase with age (up to 65), [88-92] with onset typically occurring in the third decade of life.[88, 92] Race and ethnicity have also been investigated and the data supports the observation that Caucasians, Western Europeans and North Africans are more likely to experience LBP than African Americans, Caribbeans and Latin Americans.[88, 93] However, reports of gender prevalence for LBP are vastly inconsistent.[88-90, 93, 94] Age, race, and gender have also been studied in persons with LLA. Traumatic amputations commonly occur in a younger population,[95] with as many as 63% of military service members with LLA being less than 30 years of age.[96] Non-traumatic LLA secondary to various pathological conditions such as diabetes mellitus and cancer are more frequently seen in individuals greater than 60 years of age.[95] In a study of 255 patients with traumatic and non-traumatic LLA between the ages of 19-86, age was shown to be modestly but significantly correlated (r =.12, p =.05) with whether participants experienced LBP.[97] Distinct gender and race features have also been reported in previous research with the majority of patients with traumatic and non-traumatic LLA being male[98, 99] and Caucasian.[99, 100] However, whether these demographic characteristics are associated with higher prevalence of LBP experience after LLA remains unexamined.

Obesity has also been identified as a strong risk factor for LBP in the general population.[89, 90, 101] In patients with LLA, obesity appears to be prevalent and dependent on the level of amputation, with 38% of persons with transtibial, 48% of persons with transfemoral, and 64% of persons with bilateral amputation presenting with noticeable clinical signs of obesity.[102] In support of the potential link between obesity and LBP, patients with LLA and LBP appear to have body mass index ratios above 50% of the recommended ratio compared to their counterparts without LBP.[13] The excess weight gain appears to be substantial and most common within the first two years after LLA,[103] which may be attributed to the sedentary lifestyle immediately after amputation.[104 13]

Maintaining a healthy weight is commonly a challenge for patients with LLA due to difficulties associated with participating in exercise and sports activities.[10] Given the previous reports of increased risk of chronic LBP development as a result of inactivity in the general population,[90, 92] the reported reductions in physical activity levels after LLA[105, 106] inherently increase the risk of LBP in this patient population. While participation in recreational or competitive sports has been reported in 32-60% of patients with LLA,[96, 107] there are fewer barriers in younger individuals who are more likely to achieve higher levels of physical performance due to accelerated rates of recovery and early fitting of running-specific prostheses.[108, 109] Conversely, up to 46% of older persons with LLA become non-ambulatory one year post-amputation, which may place them at a higher risk of developing chronic LBP.[110] Although clinicians often attribute functional difficulties in this population to problems with the amputation and the prosthesis, LBP can also independently restrict activity levels in patients with LLA and warrants further investigation.[111, 112]

A number of physical characteristics have also been identified as risk factors for non-specific LBP in the general population, such as altered muscle strength/endurance, leg length discrepancy, or previous history of LBP.[92, 113-117] In persons with LLA, greater iliopsoas muscle length but reduced back extensor strength and endurance have been associated with the presence of LBP.[15] Leg length discrepancy as a source of structural malalignment, including pelvic obliquity and functional scoliosis,[118] has also been suggested as a potential cause of LBP after LLA but with conflicting supporting evidence. For example, in a study of 113 Finnish war-disabled service members with amputation, those with unilateral LLA and LBP with mild and occasional symptoms had a mean leg length discrepancy of 6.1 mm as compared to a 21.7 mm discrepancy for those who reported severe and constant symptoms.[119] In other studies, however, no correlations have been reported between LBP and leg length discrepancy in persons with LLA.[120, 121] Previous history of LBP in the general population has also been suggested to almost double the risk of future episodes of LBP.[116, 117] In patients with LLA and LBP, however, only less than 20% recall having LBP prior to their amputation,[8, 9] and in most cases directly attribute their LBP to their LLA.[10]

Psychological Factors

Beyond biologic factors, as an individual with LLA reintegrates within the community, additional psychological factors can affect the risk for LBP and its eventual chronicity. Presence of psychological risk factors in the general LBP population are suggested to affect the frequency and intensity of follow-up medical care and the choice of interventions; whereas in their absence the patient has enhanced potential for quick recovery.[122] Recent evidence further suggests that targeting psychological factors in patients with LBP, particularly when they are at high levels, does seem to lead to more consistently positive results than either ignoring them or providing omnibus interventions regardless of psychological risk factors.[123] In the general population, moderate to strong associations have been reported between onset and chronicity of LBP with various psychological conditions such as depression, pain catastrophizing, passive coping strategies, fear-avoidance beliefs and somatization.[122-126] However, the influence of these psychological factors on the experience of LBP after LLA has not been fully evaluated.

Depressive mood has been related to the onset of LBP, higher levels of LBP intensity, poorer treatment outcome and transition from acute to chronic LBP.[127, 128] To this end, depressive mood has also been reported as a significant predictor of the level of LBP intensity and bothersomeness in patients with LLA.[12] Given the much higher rates of depression in patients with LLA as compared to the general population,[129, 130] presence of depressive mood may play an important role in the increased risk for chronic LBP in this patient population. There is also a growing recognition that particular kinds of coping mechanisms such as pain catastrophizing (defined as the tendency to focus on, ruminate, and magnify pain sensations) are correlated with the transition from acute to chronic LBP and may be associated with poor treatment outcomes in the general population.[128, 131] Prospective studies suggest that passive coping strategies, especially high levels of pain catastrophizing before an amputation, are associated with development and higher intensity of phantom limb pain and disability.[132-135] However, the extent to which passive coping strategies could influence the LBP experience after LLA remains unknown.

Fear of movement or injury (kinesiophobia) is another important predictor of LBP development and chronicity that could lead to severe disability in the general population.[136, 137] This fear of movement can impede the rehabilitation process and cause dysfunctional pain-avoidance movement patterns that may lead to the development of secondary LBP after LLA. To this end, patients with higher fear-avoidance scores are more likely to have worse outcomes at 3, 6, and 12 months.[122] Although, it stands to reason that patients with LLA may develop beliefs about their condition that may cause them to become fearful of moving and engaging in daily activities, evidence of kinesiophobia in patients with LLA has not been previously evaluated.

Similarly, somatization is another prevalent psychological condition in patients with LBP that includes increased reports of widespread muscle pain located along the whole spine as well as to the legs and the head.[138] Somatization may also be related to presence of sleep disorder, anxiety, and symptoms of depression.[138] Higher somatization scores have been previously correlated with higher intensity of pain and grater disability, failure to return to work at 3 months and increased likelihood of a worse outcome at 1 year in patients with LBP.[122, 139] Evidence of somatization has also been previously reported in patients with traumatic LLA and neuropathic pain with the resulting abnormal sensory processing leading to locomotor dysfunction and body image disturbances.[140] However, a number of factors such as time since amputation, time since first prosthesis, duration of daily prosthesis use, and high prosthesis satisfaction have shown to be negatively correlated with somatization.[141] Given the evidence suggesting that psychosocial factors can influence the outcome of rehabilitation, more research efforts are warranted for developing clinical tools to identify when and how psychosocial factors could be utilized in clinical decision making to improve patient-related outcomes.[142]

Alterations in central pain processing are also influenced by psychosocial and cognitive factors such as pain catastrophizing, attention, stress, and expectation.[64] People with amputation have been reported to display more depressive symptoms, greater anxiety, lower quality of life, and emotional disturbances.[143] Further, neuropathic pain in persons with amputation has been associated with depression, post-traumatic stress disorder, and catastrophizing.[144] It has also been reported that alterations in pain sensitivity and temporal summation of pain, as well as cortical responses to painful stimuli, were modulated by pain catastrophizing.[82, 145] These psychosocial factors present in some patients with amputation and neuropathic pain, have also been associated with chronic-recurrent LBP and alterations in pain processing.[146, 147] Although no specific association was previously reported between presence of phantom limb pain and psychological symptoms in a small study,[143] strong evidence in support of the relationship between presence of psychosocial risk factors, alterations in central processing of pain, and LBP in patients with LLA remains scant.

Social Factors

The effects of social factors such as cigarette smoking, alcohol use, marital status, occupation, and income on the experience of LBP have been under extensive investigation in the general population. For example, findings from systematic reviews including cross-sectional and longitudinal studies have revealed that both current and former smokers have a higher prevalence and incidence of LBP than “never smokers”, but the association is fairly modest.[148, 149] In military personnel with amputation, 21% report smoking cigarettes on a regular basis,[150] while other studies have found that 37-48% of males with amputation are current cigarette smokers.[100, 110] Although strong evidence linking cigarette smoking and LBP after LLA is lacking; one small study reported no difference in frequency of cigarette smoking between persons with transfemoral amputations with and without LBP.[120]Alcohol consumption has also been found to be greater in those with LBP in the general population.[92] In military personnel with amputation, alcohol consumption and substance abuse, along with probable alcohol addiction, is more prevalent than in their non-amputee counterparts.[151] However, research evidence in support of the association between alcohol consumption and LBP after LLA does not currently exist. Being married is another social factors associated with higher risk of developing LBP in the general population compared to those who are divorced or single.[90] Although most reports indicate that the majority of individuals with LLA are married,[96, 150, 152, 153] marital status in at least one cohort study was shown not to be associated with either the intensity or bothersomeness of LBP in patients with LLA.[12]

Individuals with occupations involving heavy lifting/pushing/pulling and driving have historically been identified to be more prone to development of LBP in the general population. [90, [92, 154-156] As for the military population, predictors of LBP include jobs involving lifting and wearing body armor,[157] with a higher incidence seen in construction workers, auto mechanics, and law enforcement personnel.[158] However, both military and non-military individuals with LLA often return to employment in less physically demanding occupations,[150, 159, 160] which may decrease their risk of developing occupation-related LBP. Lower socioeconomic class and lower levels of education have also been found to correlate with LBP in the general population.[90] Enlisted rank and service in the Navy, Army or Air Force have been identified as risk factors for LBP in a military sample.[161] Education at or below a high school level has been reported in 27-60% of service members with amputation[96, 152] and 78% of those with amputations of dysvascular or diabetic aetiologies.[100] Of the service members with (traumatic) amputation, 31% were junior enlisted, 49% mid to senior enlisted, and 20% were officers.[96] In a sample of individuals with dysvascular or diabetic amputations, 44% reported an income of <$25,000, 37% between $25,001 and $50,000, and 19% an income >$50,000.[100] Further investigations are needed to determine the potential relationships between occupation, socioeconomic class, level of education and salary with LBP experience after LLA.

Conclusions

In the United States, an estimated 185,000 persons undergo limb amputation each year as a result of dysvascular disease (54%), trauma (45%), or cancer (1%), with the projected total number of people living with limb loss doubling to up to 3.6 million by the year 2050.[162] In general, most amputations are major LLA (excluding toes) with increasing prevalence rates due to dysvascular diseases such as diabetes mellitus.[162, 163] Despite the high prevalence of LBP after LLA, there currently exists a lack of understanding to identify any definite pathologic processes or anatomic sources of pain. A growing body of evidence from studies of LBP in the general population suggests that it is no longer appropriate to try to subclassify LBP solely using a biomedical construct, and that a successful classification system must include biomedical, psychological, and social assessments.[25] Given the multifactorial nature of LBP after LLA, a more comprehensive understanding of how amputation influences these biopsychosocial risk factors will further allow effective stratification of care for LBP after LLA, where patients are screened and placed in interventions designed to target their specific biopsychosocial risk profiles. The aim of this special communication was to integrate evidence originating predominantly from prospective studies on biopsychosocial correlates of LBP after LLA into a coherent model that could help generate new research questions and improve our understanding of the LBP experience in this unique patient population.

The proposed biopsychosocial model could be useful in identifying risk factors for early identification of patients at risk for LBP and testing the effectiveness of different approaches aimed at reducing chronic LBP-related disability after LLA. Currently, the results from psychosocial interventions for LBP in the general population consistently show only small to moderate effects.[16, 164, 165] However, a multidisciplinary approach that addresses all three components of the biopsychosocial model of LBP may provide a more appropriate solution aimed at the multifaceted nature of the LBP experience after LLA.[16] A number of prospective studies have shown that psychosocial factors influence how patients respond to rehabilitative and surgical treatment, thus indicating the interaction between physical and psychological factors are important in determining the outcome of a given treatment for LBP after LLA.[17]

Another potential approach would be to implement a stratified care approach, where patients with LLA are screened for known biopsychosocial risk factors using reliable and valid tools, and then referred to interventions designed to target their specific problem and risk profile.[16] To this end, use of a stratified approach, by use of prognostic screening with matched clinical pathways has shown promising results in management of LBP in primary care for the general population.[166] However, the current challenge to implementation of a stratified care approach is the identification and development of a validated risk factor profiles that could be used as a clinical guide to stratify patients with LLA into streams of care that optimize their chance of a good outcome for treatment of LBP. Given that some factors exert an influence on outcome regardless of treatment, whereas some only influence response to specific treatment,[16] additional clarity is needed to determine which predictors of outcome are prognostic factors and which are potential treatment effect modifiers to help guide best practice treatments and the prevention of disability.[167] Additional research and insight are needed to determine more effective approaches to mitigate or manage LBP after LLA.

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