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Effect of Unilateral Lower-Limb Amputation on Intact Limb Biomechanics: A Systematic Review

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EFFECT OF UNILATERAL LOWER-LIMB AMPUTATION ON INTACT LIMB BIOMECHANICS: A SYSTEMATIC REVIEW.

by

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ABSTRACT

The United States will perform 30,000-40,000 amputations this year (Ertl et al., 2019). As a common medical intervention, there is extensive research regarding rehabilitation strategies and post-operative care. Many studies have explored the effects of the affected limb and prosthetic intervention yet have neglected that of the contralateral limb (De Asha et al., 2014; Jones et al., 2006; Winter & Sienko, 1988). Studies have reported an increase in secondary musculoskeletal conditions among unilateral lower-limb amputees, particularly in the intact limb, indicating the need for additional research (Gailey et al., 2008). The purpose of this systematic review was to investigate the research regarding the effect of unilateral lower-limb amputation on intact limb biomechanics.

This systematic review was guided by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standards (Moher et al., 2009). All search procedures, eligibility criteria, and data extraction were defined prior to the study protocol. A comprehensive search for peer-reviewed journals was conducted through the PubMed and Cochrane Library search engines. Thirty-two articles were selected for this review, six of which stated no significant biomechanical differences between the amputees and the general population. The remaining 26 articles concluded that stability and pain avoidance strategies, asymmetric gait adaptations, atypical forces, and complex trunk movement are biomechanical compensations that contribute to secondary complications of the intact limb. Findings from this systematic review showed that pain avoidance strategies, asymmetric gait adaptations, atypical forces, and complex trunk

movements contribute towards the development of secondary musculoskeletal conditions of the intact limb.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF ABBREVIATIONS

COG	Center of Gravity
LLA	Lower-Limb Amputation
TTA	Transtibial Amputation
TFA	Transfemoral Amputation
MVC	Maximum Voluntary Contraction
CTRL	Uninjured Control Participant
FFA	First Fitted Amputee
UTA	Unilateral Transtibial Amputation

CHAPTER I - INTRODUCTION

Approximately every 30 seconds, a leg is amputated (Fakorede, 2018). Perhaps one of the oldest surgical procedures of our time, amputation, has changed the scope of medical practice regarding prosthetics and rehabilitation. There has been extensive research regarding rehabilitation protocol and post-operative care. Many studies have focused on the properties of the affected limb or prosthesis intervention, neglecting to explore the effects on the contralateral limb. Gailey et al. (2008) reported that unilateral lower-limb amputees often experience increased lower back pain, posture compensations, and are at greater risk for degenerative conditions such as osteoarthritis, particularly of the intact limb, supporting the need for additional intensive research.

Contributing research has been published regarding the quality of life for lower-limb amputees, finding that those with a unilateral lower-limb amputation commonly develop secondary musculoskeletal complications. A higher occurrence of osteoarthritis in the knee and hip of the intact limb has been reported, as well as higher rates of lower back pain among lower-limb amputees (Struyf et al., 2009). Kinematics of movements such as dynamic sitting, trunk control, range of motion, and locomotion are considered risk factors for secondary complications and are evaluated by an amputee's care team as potential areas for intervention (Standard of Care, 2011). Furthermore, assessing muscle performance and gait mechanics provides insight into asymmetries and areas of inadequate control that affect kinetics (Sanderson & Martin, 1997). Therefore, it is hypothesized that biomechanical compensations have an effect on the contralateral limb and may provide an explanation for secondary musculoskeletal complications. Thus, the primary purpose of this systematic review is to investigate the research regarding the effect of unilateral lower-limb amputation on intact limb biomechanics.

CHAPTER II – METHODOLOGY

Literature Search

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009). A comprehensive and systematic search for peer-reviewed journals published from 2000 to 2019 was performed. The literature search utilized the PubMed and Cochrane Library electronic databases. The search criteria included two independent search phrases, "effects of unilateral lower limb amputation" and "biomechanics of unilateral lower limb amputation."

Inclusion Criteria

Inclusion criteria consisted of articles that evaluated the biomechanical effects of the intact limb in human subjects with a unilateral lower limb amputation. Articles were eligible for inclusion if published between 2000 and 2019 and evaluated five or more human subjects, male and female, 18-years of age or older. Due to limited research regarding biomechanical effects of unilateral lower-limb amputations, individuals with either unilateral transfemoral or unilateral transtibial amputation were included. Additionally, both traumatic and vascular amputations were accepted. Intervention methods were not restricted and included self-selected walking speeds, sit-to-stand movements, split-belt treadmill testing, task-oriented ambulation, and step ascent and descent.

Exclusion Criteria

Articles published in languages other than English were excluded. As were articles that did not examine the biomechanics of the contralateral limb. Biomechanics was defined as the study of continuum mechanics and the effects on the body's movement and structure. In addition, articles that investigated pain management techniques, compared prosthetic or orthotic devices, or determined the validity of any biomechanical testing tools were excluded. Case studies and other systematic reviews were not included in our final literature review.

Data Extraction and Quality Assessment

The data review and extraction were performed by two independent reviewers using Covidence software, a web-based platform that helps to streamline systematic reviews (Veritas Health Innovation, 2019). Disagreements were resolved with discussion and a third independent reviewer. A quality assessment was also performed through Covidence using the NIH Quality Assessment Tool. Focusing on key concepts, an independent reviewer conducted a critical appraisal of the articles' internal validity. Each item was evaluated for potential bias, confounding factors, and study power. The NIH Quality Assessment Tool is comprised of yes or no questions (National Institutes of Health, 2014). If the reviewer determined the answer to be no, the risk of bias is deemed high, while if the reviewer determined the answer to be yes, the risk of bias is low. If the answer is unknown, the reviewer then marked unclear. Table 1 provides insight regarding the quality assessment of these studies.

Table 1 *NIH Quality Assessment (National Institutes of Health, 2014)*

Study ID	Research Question	Assessed Exposure	Outcome measure defined	Outcome assessors blinded	Loss follow -up	Confounding Variable	Defined study population	Participation rate	Inclusion and exclusion application	Sample size	Exposure of interest	Time-frame	Level of exposure	Exposure measure
Acasio et al. 2019	low	low	low	high	high	high	low	unclear	low	high	low	low	low	low
Barnett et al. 2013	low	low	low	high	low	low	low	unclear	low	high	low	low	low	low
Butowicz et al. 2019	low	low	low	high	low	low	low	unclear	low	low	low	low	low	low
Castro et al. 2014	low	low	low	high	high	low	low	unclear	low	low	high	low	low	low
Childers et al. 2014	low	high	low	high	high	high	high	unclear	low	high	low	high	low	low
Darter et al. 2017	low	high	low	high	high	low	low	unclear	low	high	high	low	low	low
De Asha et al. 2015a	low	low	low	high	high	high	low	unclear	low	high	high	high	low	low
De Asha et al. 2015b	low	low	low	high	high	low	low	unclear	low	high	high	high	low	low
Giest et al. 2016	low	low	low	high	high	low	low	unclear	low	high	high	high	low	low
Golyski et al. 2018	low	low	low	high	high	low	low	unclear	low	high	high	high	low	low
Hendershot et al. 2013	low	high	low	high	high	low	low	unclear	low	low	high	high	low	low
Hendershot et al. 2015	low	low	high	high	high	low	low	unclear	low	high	high	high	low	low
Kendell et al. 2016	low	low	low	high	high	high	low	unclear	low	high	high	high	low	low
Krupenevich et al. 2018	low	low	low	high	low	low	low	unclear	low	low	high	high	low	high
Lloyd et al. 2010	low	low	low	high	high	low	low	unclear	low	low	high	high	low	low
Mahon et al. 2017	low	high	low	high	high	low	low	low	low	low	low	high	low	low
Mayer et al. 2011	low	high	low	high	high	low	low	low	low	high	high	high	low	low

Note: Low indicates a lower risk of bias. High indicates a higher risk of bias.

Table 1 (continued)

Study ID	Research Question	Assessed Exposure	Outcome measure defined	Outcome assessors blinded	Loss follow -up	Confounding Variable	Defined study population	Participation rate	Inclusion and exclusion application	Sample size	Exposure of interest	Time-frame	Level of exposure	Exposure measure
Molina-Rueda et al. 2013	low	low	low	high	high	low	low	unclear	low	high	high	high	low	low
Molina-Rueda et al. 2016	low	low	low	high	high	low	low	unclear	low	high	low	high	low	low
Morgenroth et al. 2018	low	low	low	high	high	low	low	unclear	low	high	high	high	low	low
Murray et al. 2017	low	low	low	high	high	unclear	low	unclear	low	high	high	high	low	low
Pruziner et al. 2014	low	low	low	high	high	low	low	unclear	low	high	high	high	low	low
Pruziner et al. 2019	low	low	low	unclear	high	high	low	unclear	low	high	high	low	low	low
Rodrigues et al. 2019	low	high	low	high	high	low	low	unclear	unclear	high	high	high	low	low
Russell Esposito et al. 2014	low	low	low	high	high	low	low	unclear	low	high	high	high	low	low
Schnall et al. 2014	low	low	low	high	high	low	low	unclear	low	high	high	high	low	low
Schoeman et al. 2013	low	low	low	high	high	low	low	unclear	low	high	high	high	low	low
Selgrade et al. 2017	low	low	low	high	high	unclear	low	unclear	low	high	high	high	low	low
Shojaei et al. 2016	low	high	low	high	high	low	low	unclear	low	high	low	high	low	low
Shojaei et al. 2019	low	low	low	high	high	low	low	unclear	low	high	high	high	low	low
Silverman et al. 2014	low	low	low	high	high	low	high	unclear	high	high	high	high	low	low
Yoder et al. 2015	low	low	low	high	high	low	low	unclear	low	high	high	high	low	low

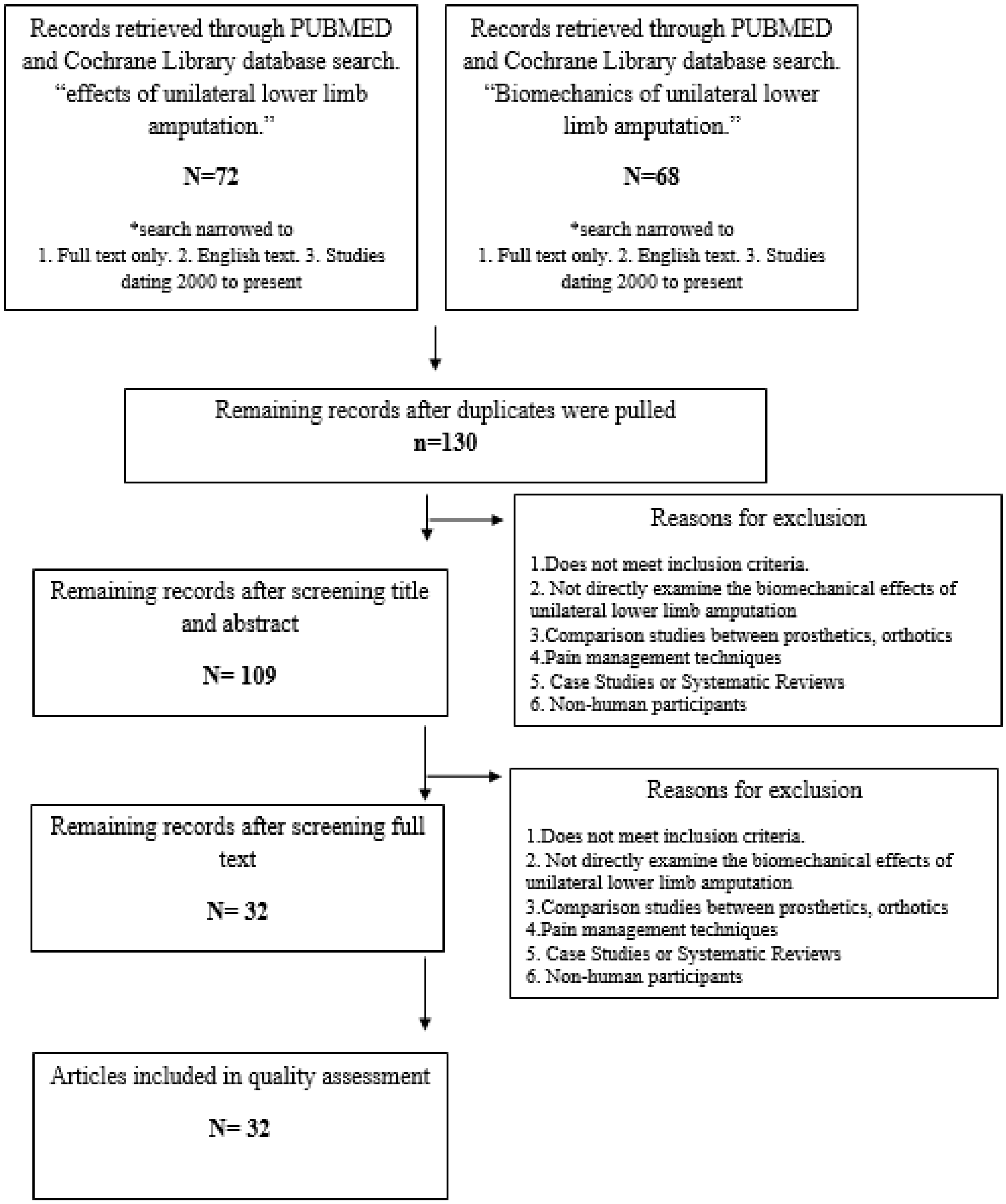
Note: Low indicates a lower risk of bias. High indicates a higher risk of bias.

CHAPTER III – RESULTS

The initial literature search resulted in 72 articles from "effects of unilateral lower limb amputation" and 68 articles from "biomechanics of unilateral lower limb amputation." After removing duplicates, Covidence identified 130 abstracts for review. A review of the title and abstract was then performed. Of these 130 abstracts, 21 were excluded due to non-unilateral lower limb amputation participants, a comparison of orthotic products or inserts, and the inability to directly measure the biomechanical effects. The full-text screening was then completed on the remaining 109 articles, which excluded 77 articles that did not adhere to the inclusion criteria. One reviewer further examined all eligible articles for bias using the NIH quality assessment tool. In sum, 32 articles were included in the systematic review. The PRISMA flowchart (see Figure 1) summarizes the number of articles identified and reviewed. The data extraction results are listed in the Covidence Evidence Summary Table 2, see appendix.

Figure 1.

PRISMA Flowchart (Moher et al., 2009).



CHAPTER IV – DISCUSSION

Summary of Findings

Out of the 32 studies reviewed, 26 reported compensations were shown to affect the intact limb's biomechanics. Findings include stability and pain avoidance, asymmetric gait adaptations, atypical forces, and complex trunk movement. The six remaining studies reported no significant biomechanical difference between the amputee population and non-amputee control participants.

Stability and Pain Avoidance Strategies

Four studies reported that unilateral lower-limb amputees rely on the intact limb to preserve stability and avoid the pain of the affected limb. One study further observed the use of the intact limb to help reduce fatigue (Mayer et al., 2011). Another study noted reliance on the intact limb to enhance body progression and better stability during task-oriented movements (Kendell et al., 2016). A study performed by Rodrigues et al. (2019) concluded that amputees alter the locomotor activity to stabilize the upper body. Barnett et al. (2013) reported that balance improved over time, but amputees heavily rely on vision.

Asymmetric Gait Adaptations

Eight articles observed asymmetric gait adaptations. Reported findings included reduced intact step length with reduced speed (Morgenroth et al., 2018), maladaptive movement with 90-degree turns (Golyski & Hendershot, 2018), knee extension asymmetry (Lloyd, et al., 2010), and step width variability with larger ground reaction forces and instability due to larger trunk velocity (Mahon et al., 2017). During a split-belt study, amputees adjusted to changing speeds the same as the uninjured control participants but relied on the COM displacement strategy, reducing metabolic power (Selgrade et al., 2017). De Asha and Buckley (2015a) observed an increase in minimal toe clearance on the intact limb, but not on the affected side. Additionally, increased plantar pressure and temporal foot roll-over were noted by Castro et al. (2014). One study observed decreased knee extension of the prosthetic during ambulation and an increased extension of the intact limb, potentially developing due to protective compensations of the affected limb (Molina-Rueda et al., 2013).

Atypical Forces

Numerous articles reported higher forces on the intact limb with ambulation or other progressive movements. Higher peak axial contact forces (Silverman & Neptune, 2014), peak vertical ground reaction force loading rates (Pruziner et al., 2014), and peak anterior-posterior force on intact limb were all founded (Giest & Chang, 2016). A retrospective study showed increased mechanical work on the intact limb over time (Butowicz et al., 2019). Another study found faster latencies and increased weight placed on the intact limb during an unexpected surface disturbance (Molina-Rueda et al., 2016). One study investigated the effects of vertical jumps, reporting higher landing forces on the intact limb (Schoeman et al., 2013). Atypical motion and muscle forces were investigated among one study, finding higher muscle forces relating to the obliques and erector spinae muscles during bilateral stance, and greater muscle force of the intact-side obliques. A more significant finding of this study was the increased lateral bending toward the residual side during a single-limb stance (Yoder et al., 2015).

Complex Trunk Movements

Complex trunk movements are observed among the many studies. In one study, anterior-posterior shear forces were found to be more significant among unilateral lower-limb amputees during the sit-to-stand movement (Shojaei et al., 2019). Also addressing biomechanics regarding sit-to-stand, another study observed altered lumbosacral movement with increased trunk motions (Hendershot & Wolf, 2015). One study reported forward trunk lean when carrying a load (Schnall et al., 2014). Investigating downward and upward slope walking, one study showed shorter stride length and wider stride width, along with a more extensive tri-planar trunk range of motion and anterior lean of the trunk and pelvis (Acasio et al., 2019). Another study recorded altered trunk muscle recruitment during an intact limb stance, specifically noting co-activation of antagonist muscle groups (Shojaei et al., 2016). The neurological behaviors of trunk mechanics were addressed by one study, finding a 20% decrease in trunk stiffness compared to the nonamputee control group and bilateral asymmetric trunk mechanics (Hendershot et al., 2013). Another study evaluated step ascent and descent, observing increased trunk forward and lateral flexion with asymmetric loading patterns in the lower-limb joints (Murray et al., 2017).

Conflicting Studies

Conversely, the remaining studies reported no significant biomechanical differences among unilateral lower-limb amputees and an uninjured control group. Pruziner et al. (2019) and Darter et al. (2017) concluded that there were similar changes in gait mechanics and locomotor adaptations among amputees and the non-amputee control participants, both established a more stable gait pattern while performing a task.

Each study analyzed locomotor performance by comparing the reaction time and adaptability of amputees versus nonamputees. Darter et al. (2017) further investigated confounding factors, such as the reliance on handrails among the amputee participants, which may have altered the outcomes. Childers and Kogler (2014) found that kinetic symmetry did not correlate to kinematic symmetry, challenging the traditional rehabilitation protocol. However, the authors cited significant compensations at the knee and hip made to maintain force and noted worsening asymmetry between the amputated and intact limb during shorter crank arm conditions. Investigating the sound limb, Russell and Wilken (2014) reported no evidence of degenerative risk-factors in early prosthetic users, specifically with knee osteoarthritis. However, the authors admitted to not measuring cartilage or considering additional risk-factors. Authors also theorized that unilateral lower-limb amputees develop degenerative conditions due to altered gait and biomechanics over time, encouraging a focus on an onset timeline. One longitudinal study reported that higher knee forces are suspected to be the result of compensation mechanisms and pain aversion strategies developing over time, noting walking mechanics are unchanged in participants during the initial six-months post-amputation (Krupenevich et al., 2018). The authors suggested that gait adaptations result only from confounding factors such as changes in body weight or physical activity levels.

Future Direction and Limitations

It is suggested that future research is needed to investigate the timeline regarding the onset of secondary musculoskeletal complications. Additionally, subsequent research should compare amputation type, traumatic versus vascular. Exploring differences in post-amputation care and complications between traumatic and vascular causes could provide insight into additional confounding factors. A significant limitation of this systematic review was the population size of all studies. The majority of the studies had less than 20 participants, including the nonamputee control group, making it difficult to extrapolate the data to the general population. Due to the limited studies regarding unilateral lower-limb amputees, both transtibial and transfemoral amputations were included in this review. Including both may also be viewed as a limitation because of the inherent anatomical differences between the two subgroups. Similarly, both vascular and traumatic types of amputees were included in this study to increase the breadth of literature reviewed, but this also presents limitations due to existing comorbidities. This, including transtibial and transfemoral amputations, adds additional limitations.

CHAPTER V - CONCLUSION

Findings from this systematic review showed that pain avoidance strategies, asymmetric gait adaptations, atypical forces, and complex trunk movements lead to increased reliance and stress on the intact limb. Cumulatively, findings indicate that the identified articles' biomechanical compensations contribute towards the development of secondary musculoskeletal conditions of the contralateral side. Based on these results, clinicians can suggest targeted therapies to address an individual's observed compensations. Additionally, clinicians must expect adaptations to form over time and note the development of any atypical biomechanics. Finally, further research comparing traumatic and vascular amputation differences is warranted, as is investigating the onset timeline of secondary musculoskeletal conditions.

APPENDIX– Covidence Evidence Summary

Table 2 *Covidence Evidence Summary (Veritas Health Innovation, 2019)*

Reference	The Purpose of the study was to:	Participant Characteristics	Intervention	Key Findings
Acasio et al. (2019)	evaluate altered trunk and pelvic motions would lead to greater spinal loads during slope walking	Sixteen military male unilateral transfemoral amputees. Age: 32.3 (5.9) years, stature: 179.0 (6.4) cm, body mass: 86.3 (10.0) kg.	Walking a 10 m slope at self-selected pace. Upslope and downslope set at 10 degree incline/decline.	Downslope vs. upslope: shorter stride times ($p < 0.001$) and stride lengths ($p = 0.001$), and larger stride widths ($p = 0.007$). Upslope vs downslope: Tri-planar trunk ROM were larger ($p < 0.004$). Pelvis ROM was larger only in the frontal plane (p = 0.002). Larger ($p < 0.001$) anterior lean of both the trunk (15.0 [6.8]°vs. 3.0 [4.7]°) and pelvis (25.7 [7.8]°vs.14.2 [4.3]°.Peak ML shear forces ($p = 0.011$), AP shear ($p = 0.33$) and compression ($p = 0.28$) forces were similar between inclinations . Peak local muscle forces were also larger ($p = 0.010$), global muscle forces were similar ($p = 0.35$) between inclinations.
Barnett et al. (2013)	evaluate postural response during perturbed and volitional balance tasks	Seven males- 18 years of age or older; vascular and nonvascular causation.	Sensory organization test and limits of stability test	Balance and somatosensory input improved after discharge but relied heavily on vision ($p = 0.01$). Endpoint COG and directional control increased ($p \leq 0.36$).
Butowicz et al. (2019)	evaluate joint powers and mechanical work of unaffected leg during the first year of independent ambulation	Nine males with traumatic LLA. 6 transtibial, 3 transfemoral. Retrospectively analyzed.	Instrumented gait analysis	No differences regarding positive and negative work at joints in the sagittal or frontal plane ($p > 0.038$). No differences seen in percent contribution by joints ($p > 0.32$).
Castro et al. (2014)	compare plantar pressures, temporal foot roll-over, and ground reaction forces between unilateral transfemoral amputees and abled body	Fourteen transfemoral amputees and 21 abled body participants. Mean age of 56.7 years of age +- 11.7 years and mean body mass of 71.4 -11.7 kg.	Walk at self-guided pace	Lower in the amputated limb: thrust, braking, propulsive peaks, propulsive impulses ($p <.05$). Higher in the amputated limb: pressure peaks in the lateral rearfoot and medial, lateral midfoot. ($p <.05$). Differences found between amputated limb, sound limb, and able-bodied participants: temporal foot roll-over ($p <.05$).
Childres et al. (2014)	observe kinematic and kinetic asymmetries during a propulsive task, i.e., stationary cycling	A group of 8 male recreational cyclists with TTA (body mass [mean ± standard deviation]: 81.3 ± 16.1 kg, height: 1.84 ± 0.09 m, age: 33.7 ± 10.0 yr.)	evaluating kinematics by adjusting length of crank arm to 162mm on amputated side	Reduction in hip and knee range of motion in the amputated limb versus the intact limb. No join kinematic differences seen between intact and amputated limb. Asymmetries did not differ for baseline and CRANK conditions.

Table 2 (continued).

Darter et al. (2017)	observe the impairment of locomotor adaptability in unilateral amputee	Ten with unilateral Transtibial Amputation - 8 persons with no amputee	walking on a split-belt treadmill with the parallel belts running at the same (tied) or different (split) speeds	Step length, limb excursion and stance time were highly symmetric during the tied baseline walking regardless of group. Whereas, large step length (all p <.01), limb excursion (all p <.01) and stance time (all p <.01) asymmetries were exhibited by each group at the start of split adaptation. Stance time symmetry was no different at the start of tied post-adaptation walking in the persons without an amputation (p = .58) but was for persons with TTA (p <.01). Results indicated persons with TTA were less perturbed during early split adaptation (walked more symmetrically) than the persons without an amputation (p = .02). No difference in step length symmetry was found among the persons with TTA based on belt assignment (Fig 5) during baseline (p = 0.06), split adaptation (p = 0.83) or tied post-adaptation walking (p = 0.16). Stance time symmetry did improve in persons with TTA during tied post-adaptation walking (p <.01), but not in persons without an amputation (p = .11).
De Asha et al. (2015)	determine the effects of walking speed on minimum toe clearance and on the temporal relationship between clearance and peak swing-foot velocity in unilateral trans-tibial amputees	A total of 10 physically active male UTAs (mean ± standard deviation (SD) age = 48 ± 11.7 years, mass = 86 ± 17.7 kg, height = 1.78 ± 0.06 m)	Walking different speeds: Slow, customary, fast. 0.93 ± 0.12 ms−1, 1.13 ± 0.17 ms−1 and 1.36 ± 0.27 ms−1	Toe clearance on the prosthetic side was reduced but walking speed did not increase. No significant difference in toe clearance between events.
De Asha et al. (2015)	determine the effects of laterality, compared to side of amputation, on amputees' obstacle crossing performance. and Knee proprioception for both limbs	Nine, otherwise healthy, UTAs (mean (SD) age 48.3 (13.7) years; height 1.78 (0.09) m; mass 86.7 (9.4) kg; time since amputation 20.1 (15.3) years, range 5–51 years, one female. All traumatic amputees	Walking over one of three sized obstacles	All participants reported leading with preferred lead-limb despite amputation.
Geist et al. (2016)	determine the gait transition speed of persons with unilateral, transtibial amputation donning a passive-elastic prosthesis and assess whether a mechanical limit of their intact side plantar flexor muscles is a major determinant of their walk-to-run transition	Subjects included 10 healthy, unilateral, transtibial amputee (AMP) subjects (5 males, 5 females; amputation: 3 elective due to congenital deformity, 7 traumatic; mean age±SD: 26.7±4.5 years; mass: 67.4±14.6 kg; sound leg length: 91.5±5.6 cm) and 10 healthy, able-bodied matched control (CON) subjects (5 males, 5 females; age: 29.6±6.9 years; mass: 67.2±10.0 kg; leg length: 91.1±5.4cm)	walking at speeds 50, 60, 70, 80, 90, 100, 120, and 130% of that gait transition speed	Amputees transitioned between gaits slower than able-bodied controls (1.73±0.13 and 2.09±0.05m/s respectively, p < 0.01). Increased with speed in able-bodied controls: Peak anterior-posterior propulsive force until preferred transition speed achieved. Observed decreased in higher speeds (110%: 0.27±0.04 > 120%: 0.23±0.05BW, p < 0.05). Anterior-posterior propulsive forces higher on the intact limb of amputees during walking speeds above preferred gait transition (100%: 0.28±0.04 < 110%: 0.30±0.04BW, p < 0.05).

Table 2 (continued).

Golyski et al. (2018)	characterize proximal compensations using inter-segmental momenta and coordination during transient (90-degree) turns among persons with LLA	Eight persons with unilateral LLA of traumatic etiology (four with transtibial amputation [TTA], three with transfemoral amputation, and one with knee disarticulation [TFA]) and five persons without LLA (uninjured controls; CTRL)	Performing 20 turns involving a 90-degree change in direction to the left and right	TFA performed 32 step turns and 28 spin turns. TTA performed 51 step turns and 20 spin turns. Differences between uninjured control and amputees: Frontal plank trunk-pelvis range of motion was smaller in amputees (LLA: 11.4 (3.5), CTRL: 15.3 (6.3)°; *p* = .004). Trunk-pelvis range of motion during step turns was larger in amputees sagittal plane (LLA: 8.9 (2.6), CTRL: 6.5 (3.9)°; *p* = .047). Larger frontal plane trunk RAMP (*p* <.001), and pelvis RAM (*p* =.047) observed among amputees.
Hendershot et al. (2013)	determine the effects of LLA on several aspects of trunk mechanical and neuromuscular behaviors	Eight males with unilateral LLA – four transtibial (3 right leg, 1 left leg) and four transfemoral (2 right leg, 2 left leg) – and eight male, non-amputation controls	performed standing maximum voluntary contractions (MVC) in trunk extension and left/right lateral bending, with the pelvis restrained	Trunk stiffness and maximum reflect force were 24% and 23% lower among amputees and non-amputation controls during anteriorly-directed perturbations. Maximum reflex force was 8% later in amputees. Trunk stiffness and maximum reflect force were lower among amputees during lateral perturbations (22% and 27%). Bilateral asymmetries were observed among amputees; regarding trunk stiffness and timing of maximum reflect. During perturbations dealing with spinal tissues and muscles in the contralateral limb, trunk stiffness was 20% lower and maximum reflex force was 9% later.
Hendershot et al. (2015)	quantify and compare lumbosacral joint kinetics in persons with and without traumatic unilateral TFA during sit-to-stand and stand-to-sit movements	Nine military males with unilateral TFA - 9 uninjured military male controls. At the initial visit, mean (SD) age, stature, and body mass for the participants with TFA were 27.9 (5.4) years, 178.9 (5.5) cm, and 85.2 (10.9) kg, respectively. Corresponding values for the nine uninjured controls were 27.4 (3.6) years, 183.2 (7.7) cm, and 86.2 (6.2) kg (all p values >0.21). Amputations were the result of traumatic injuries.	Participants performed five consecutive sit-to-stand (and stand-to-sit) movements from (to) an arm- and backless stool with a solid (i.e., not cushioned) seat surface; stool height was adjusted so that each participant's thighs were in a horizontal position and knees in 90° of flexion	Sit-To-Stand: Total time to complete the sit-to-stand movements was similar (p > 0.15) between persons with TFA and uninjured controls, regardless of prosthetic knee type, at 1.88 (0.36) and 1.73 (0.27) s, respectively. Prior to seat-off, peak trunk flexion angular velocities were 40.5 (21.5), 48.9 (24.7), and 30.3 (15.5)8/s for uninjured control, TFA with PK, and TFA with C-Leg groups, respectively; corresponding peak trunk lateral flexion angular velocities during seat contact were 5.7 (3.8), 9.9 (10.2), and 14.3 (11.7)8/s. At the instant of seat-off, trunk forward/lateral flexion angles were 37.3 (7.9)/2.3 (1.8), 50.4 (16.3)/2.9 (1.9), and 45.8 (12.9)/3.3 (2.3)8, for uninjured control, TFA with PK, and TFA with C-Leg groups, respectively. Stand-to-sit: Total time to complete the stand-to-sit movements was slightly longer (p = 0.041) among persons with TFA vs. uninjured controls, at 2.22 (0.34) and 1.96

Table 2 (continued).

				(0.36) s, respectively, but similar (*p* = 0.52) between knee devices. Peak joint moments and powers were again larger (all *p* < 0.001) among TFA with PK and C-Leg devices relative to uninjured controls. Joint moments and powers were again largest in the sagittal plane and frontal and transverse plane kinetics were also larger among persons with TFA relative to uninjured controls. In contrast to sit-to-stand movements, however, sagittal joint powers were not significantly (*p* > 0.15) different between groups.
Kendell et al. (2016)	determine the gait adaptations in transfemoral amputees across various walking conditions	Eleven individuals with unilateral transfemoral amputations - o were then contacted via mail and invited to participate. The mean age was 57±13years, mean mass was 75±10kg, functional levels were K3–K4,and no participants used walking aids	Navigating rigid and soft ground, ramp, and stair conditions	Greater on the intact limb versus prosthetic limb: medial-lateral center of pressure direction change, sensor cell loading frequency, double support time.
Krupenevich et al. (2018)	evaluate a longitudinal assessments of knee joint kinetics to assist with identifying the origin or progression of such loads on intact limb.	Eight male Service Members with traumatic unilateral lower limb loss (3 transfemoral/5 transtibial). ; 26 ± 5 yrs., 1.76 ± 0.04 m, 83.8 ± 13.5 kg	Walking at self-selected speed and cadence, at 0, 2, and 6 months following initial independent ambulation.	Significant time effect on stride length (*p* = 0.047). No pairwise differences, No effect observed; time on the peak (*p* = 0.666), loading rate (*p* = 0.336), impulse of knee adduction (*p* = 0.992), peak knee flexion movement (*p* = 0.128), peak or loading rate of vertical ground reaction forces (*p* = 0.485 / *p* = 0.130).
Lloyd et al. (2010)	evaluate strength asymmetry. It is hypothesized that strength asymmetry would positively correlate with gait variable asymmetry and intact side gait variables associated with osteoarthritis risk	Eight unilateral transtibial amputees (4 trauma, 2 vascular, one due to cancer, one due to infection) and 8 abled bodied participants.	Walking on the runway at self-selected pace. Resistance for strength training	Asymmetry was greater in the amputee group than abled bodied control (four out of six). Asymmetry: Knee extension strength, knee adduction moment load rate (rho=0.714), knee flexion strength, vertical ground reaction force on intact limb (rho=0.643).

Table 2 (continued).

Mahon et al. (2017)	evaluate altered body structures that occur with the loss of a lower limb can impact mobility and quality of life. Specifically, biomechanical changes that result from wearing a prosthesis have been associated with an increased risk of falls or joint degeneration, as well as increased energy demands.	Sixty-seven male traumatic transfemoral unilateral amputation and 76 male control participants aged 18-50.	Walking at self-selected speed along a 15-m walkway.	width variability (prosthetic/intact) = 0.20 (0.12–0.56)/0.26 (0.15–0.59) cm; dynamic stability margin (prosthetic/intact) = 3.72 (1.04–12.42)/3.37 (1.14–6.07) cm; peak trunk velocity = 31.92 (20.16–66.51) degrees per second. -Overuse included peak trunk ipsilateral flexion (toward prosthetic/intact) = 5.08 (0.16–13.28)/2.01 (−3.03–7.20) degrees; peak L5-S1 bending moment during stance (prosthetic/intact) = 0.47 (0.24–1.13)/0.37 (0.11–0.64) Nm/kg; first peak knee abduction moment (prosthetic/intact) = 0.29 (0.11–0.57)/0.34 (0.07–0.68) Nm/kg. vGRF impulse during stance (prosthetic/intact) = 0.47 (0.40–0.57)/0.56 (0.42–0.81) units bodyweight-second; and mean vGRF loading rate (prosthetic/intact) = 8.57 (1.28–15.28)/11.91 (6.37–18.89) units bodyweight per second. Peak trunk ipsilateral rotation (toward prosthetic/intact) = 4.48 (−2.45–11.50)/5.17 (−2.78–13.26) degrees; leading limb external mechanical work (prosthetic/intact) = −0.10 (0.03 to −0.25)/−0.13 (0.06 to −0.41) J/kg; and oxygen cost = 0.18 (0.09–0.30) mL/kg/m. Individuals with TF are single limb stance test = 31.7 (3.3–36.7) seconds. Edgren side-step test = 13.0 (7.0–18.0) m; t-test = 29.1 (21.4–77.8) seconds; Illinois agility test = 41.0 (27.7–84.6) seconds; and total CHAMP = 20.0 (3.0–23.0). The median (range) distance walked by individuals with TF for the 6-minute walk test was 509 (360–704 m).
Mayer et al. (2011)	examine adaptation strategies in balance following dysvascularity-induced unilateral tibial amputation in skilled prosthetic users and first fitted amputees.	Skilled prosthetic users: 8 male, 2 female aged 61.1 +- 10 years. New prosthetic users: 12 male, 6 female aged 64.8 +- 9.5 years. Vascular causation	20 s quiet standing using a stabilometry system with eyes-open on both legs or on the non-affected leg(s)	FFA had greater postural sway in bilateral stance (27.8% p=.0004). -FFA had a smaller postural sway when standing on a non-affected leg (*p* = 0.028).
Molina-Rueda et al. (2013)	quantify the motor adaptations in the frontal plane made by unilateral transtibial amputees.	Fifteen unilateral transtibial amputees aged 56.33 +- 14 years. 15 non-amputees 47.6 +- 14 years.	Gait analysis was performed using the VICON MOTION SYSTEM	Amputees had reduced hip abductor moment during stance phase. Valgus moment was reduced in the prosthetic limb compared to sound limb and non-amputee control. Thorax range of motion in the frontal plane was increased on the prosthetic side.

Table 2 (continued).

Molina-Rueda et al. (2016)	analyze the automatic postural reaction in response to unexpected surface perturbations in a sample of subjects with traumatic and vascular UTA and to compare these observations with those for a group of healthy subjects.	A total of 9 men with traumatic UTA aged 37-67, 7 men with vascular UTA aged 39-68, and 10 control subjects without amputation aged 46-61.	The motor control test was used to assess the participants' automatic postural responses to unexpected surface perturbations	Traumatic amputees coped with faster latencies under their sound limb in medium backward and forward perturbations (medium-backward: P 1⁄4 .004; medium-forward: P 1⁄4 .037). Traumatic amputees managed faster responses to medium-backward (P 1⁄4 .017 versus right control limb; P 1⁄4 .046 versus left control limb) and large backward (P 1⁄4 .021 versus right control limb) and medium-forward (P 1⁄4 .012 versus right control limb; P 1⁄4 .043 versus left control limb) perturbations in their sound limb. Traumatic amputees bore more weight through sound limb during medium and large backward translations (P 1⁄4 .028 and P 1⁄4 .045, respectively).
Morgenroth et al. (2018)	to determine whether intact limb loading differed between transfemoral amputees and non-amputee controls during down slope ambulation, and the compensatory strategies transfemoral amputees used to modify intact limb loading.	Five transfemoral amputees aged 26 +- 5.8 years. 5 non-amputee controls aged 23.8 +- 2.6 years.	Two prosthetic knee types used for decline walking on ramp	There were no significant differences in intact limb loading between amputees and non-amputee controls
Murray et al. (2017)	to determine biomechanics compensations of the trunk and lower extremities during high demand tasks.	Nine diabetic/transtibial amputation caused by vascular issues, 10 diabetic and 11 healthy. Aged 50-85.	Step ascent and descent	During step ascent and descent, the transtibial amputation group exhibited greater trunk forward flexion and lateral flexion compared to the other two groups ($p < 0.016$), which resulted in greater low back moments and asymmetric loading patterns in the lower extremity joints.
Pruziner et al. (2019)	evaluate temporospatial gait mechanics and cortical dynamics in a population with and without unilateral transtibial limb loss.	Fifteen with unilateral transtibial amputation and 15 without	Performing concurrent tasks while walking on level treadmill and seated. low demand and high demand.	Post hoc analysis indicated that participants demonstrated a wider base ($p = 0.003$) and decreased variability ($p = 0.016$) in their stride width when completing the high-demand task compared to the no-demand task.
Pruziner et al. (2014)	determine whether biomechanical variables of joint and limb loading are larger in the intact limb of servicemembers with versus without unilateral lower-limb loss and whether intact limb loading differs between shorter versus longer durations of	Thirty-two individuals with unilateral transtibial limb loss, 49 with unilateral transfemoral limb loss, and 28 without limb loss	self-selected velocity along a 15-m walkway until at least five clean foot strikes were recorded per leg;	Intact limb mean and peak vertical ground reaction force loading rates (median [range; 95% confidence interval]) were larger for transtibial subjects with ≤ 6 months of experience ambulating with a prosthesis versus non-amputee control subjects. I Intact limb mean and peak vertical ground reaction force loading rates were also larger in subjects with transfemoral limb loss with ≤ 6 months and ≥ 2 years of experience

Table 2 (continued).

	ambulation with a prosthesis.			ambulating with a prosthesis versus non-amputee control subjects. Intact limb vertical ground reaction force impulses were also larger among both groups of transfemoral subjects versus non-amputee control subjects, respectively.
Rodrigues et al. (2019)	analyze gait variability and stability of individuals with amputation walking on upward (8%), horizontal (0%), and downward (− 8%) inclines, by using linear and nonlinear descriptors.	Unilateral transtibial amputees (TTA, N = 12); unilateral transfemoral amputees (TFA, N = 13); abled-bodied control group (CT, N = 15).	Walking on treadmill at specified inclines or declines at preferred walking speed	The TTA group exhibited motor adaptability similar to the CT group, despite altered somato- sensory feedback and functional impairments imposed by the use of a prosthetic limb. The TTA group presented greater potential to modify locomotor strategies to meet the demands of walking on inclines in relation to the TFA group, which suggests that the level of amputation had a direct relationship with the results found.
Russell et al. (2014)	compare limb loading between 1. passive and powered ankle–foot prosthesis, 2. sound and amputated limbs, and 3. individuals with amputations in the relatively early stages of prosthetic use and controls.	Ten young, active individuals with unilateral transtibial amputation (9 males, 1 female) and 10 abled-bodied controls	Individuals walked at three different controlled speeds	The powered prosthesis did not decrease the sound limb's peak adduction moment or its impulse, but did decrease the external flexor moment, peak vertical force, and loading rate as speed increased. The powered prosthesis decreased the loading rate from non-amputee controls. The sound limb did not display a significantly greater risk for knee osteoarthritis than the intact limb or than non-amputee controls in either device.
Schnall et al. (2014)	quantify and compare temporal-spatial and kinematic gait parameters in servicemembers with and without unilateral TTA during several military-relevant loaded walking conditions.	Ten male servicemembers with unilateral transtibial amputation (TTA) and 10 uninjured male controls. Aged 18-35	6 treadmill walking tests that consisted of speeds 1.34 and 1.52 and three loads: none, 28.7 kg and 32.7 kg.	Persons with TTA exhibited biomechanical compensations to carry loads that are comparable to those observed in uninjured individuals. Distinct gait changes unique to those with TTA, notably, increased dorsiflexion (deformation) of the prosthetic foot/ankle, less stance knee flexion on the prosthetic limb, and altered trunk forward lean/excursion.
Schoeman et al. (2013)	evaluate loading symmetry during vertical jump landings between a person with amputation’s intact and prosthetic limbs was assessed to determine the role of each limb in controlling the downward momentum of the center of mass during landing.	Six participants with unilateral transtibial amputation (TTA), 5 male and 1 female, aged 33-49 years. Ten nondisabled participants,9 males and 1 female, aged 19-35 years.	10 maximal vertical jumps. Highest jump was analyzed	Participants with TTA performed quasi unilateral landings onto the intact limbs, either resulting from the incapability of the prosthetic ankle to plantar flex or increased residual-limb knee and hip flexion. In the loading phase, the participants with TTA displayed reduced prosthetic side peak vertical forces ($p = 0.04$) along with reduced prosthetic-side ankle range of motion ($p < 0.001$), extensor moments ($p = 0.03$), and negative work generated ($p = 0.00$). Individual asymmetries were evident in the peak vertical force magnitudes

Table 2 (continued).

				(SI = 51%–140%), duration from touchdown to peak vertical force (SI = 52%–157%), ankle joint angles at touchdown (SI =100%–538%), ranges of motion (SI = 147%–200%), knee (SI =66%–179%) and hip (SI = 87%–132%) extensor moments, and work done at the ankle (SI = 155%–199%) and hip (SI = 83%– 204%). High peak forces intact limb and prosthetic limb) from significantly lower ($p < 0.001$) landing heights than the nondisabled participants indicate a potential injury risk associated with landing for people with TTA.
Selgrade et al. (2017)	determine how joint work changes as subjects adapt to split-belt walking; and, to explore biomechanical compensation mechanisms trans-tibial amputees use during split-belt walking.	Eight trans-tibial amputees (6 male, 1 congenital, 7 traumatic, BW:80.4±16.9kg, intact leg length:92.0±6.4cm) and eight matched uninjured controls (6 male, BW:81.5±14.1kg, leg length:91.8±4.7cm)	Subjects completed three baseline trials with belts at the same speed (tied-belt at 75%, 150%, and 75%PWS), then walked 15 minutes in a split-belt condition, with one belt at 150%PWS and one at 75%PWS.	Intact leg work, ankle work, and hip work in amputees were unchanged during adaptation. All subjects increased collisional energy loss on the fast belt, but did not increase propulsive work. This was possible because subjects moved further backward during fast leg single support in late adaptation than in early adaptation, compensating by reducing backward movement in slow leg single support. Amputees showed reduced metabolic power.
Shojaei et al. (2019)	determine differences in trunk muscle forces and spinal loads between persons with and without lower limb amputation when performing sit-to-stand and stand-to-sit tasks.	Ten males with unilateral transfemoral lower limb amputation and 10 male control participants aged 27.9 +-5.4 years.	Sit to stand and sit to stand activities	The peak compression force, medio-lateral (only during stand-to-sit), and antero-posterior shear forces were respectively 348 N, 269 N, and 217 N larger in person with vs. without amputation. Persons with amputation also experienced on average 171 N and 53 N larger mean compression force and medio-lateral shear force, respectively.
Shojaei et al. (2016)	evaluate the increases in trunk muscle forces would, in turn, result in larger spinal loads.	Twenty males with transfemoral amputation aged 29.2 +- 4.8 years. 20 male controls aged 28.1 +- 4.8 years.	15 m walkway at self-paced	Trunk muscle force and spinal load maxima corresponded with heel strike and toe off events, and among persons with amputation, were respectively 10–40% and 17–95% larger during intact vs. prosthetic stance, as well as 6–80% and 26–60% larger during intact stance relative to uninjured controls.
Silverman et al. (2014)	compare knee joint contact forces and the muscles contributing to these forces between amputees and non-amputees during walking using forward dynamics simulations.	Fourteen individuals with transtibial amputation (11 traumatic, 3 vascular) aged 45.1 years +- 9.1 years. Average time since amputation was 5 years. 10 non-amputees aged 34.1 years +- 13 years.	walking overground at 1.270.06 m/s	The residual leg stance simulation had an average difference of 7.111 (2SD¼10.541) across all degrees of freedom and 5.65% body weight (BW, 2SD¼5.35%BW) from the average amputee experimental data. The intact leg stance simulation had an average difference of 5.271 (2SD¼10.411) and 5.07%BW (2SD¼5.32%BW) from the experimental data. The non-amputee left leg stance simulation had an average difference of 4.271 (2SD¼10.821) and

Table 2 (continued).

				5.15%BW (2SD¼6.07%BW) from the average non-amputee experimental data. The net A/P joint contact force was directed anteriorly throughout the stance for all three legs (Fig. 1). Peak anterior forces were the largest for the intact leg, followed by the residual and non-amputee legs, respectively.
Yoder et al. (2015)	compare dynamic trunk–pelvis biomechanics.	Six people with Unilateral transtibial amputees, five male, one female. 43.7 years of age +- 7.7 years. At least 1 year post amputation. 6 control participants, five male, one female. 35.3 years of age +- 12.6 years.	Walking at self-selected pace across 10 m walkway	Greater lateral bending toward the residual side during residual single-limb stance ($p < 0.01$), concurrent with an elevated L4L5 joint contact force ($p = 0.02$) and greater muscle force from the intact-side obliques (p < 0.01) in people with TTA relative to able-bodied people. During both double-limb support phases, people with TTA also had a greater range of axial trunk rotation away from the leading limb, concurrent with greater ranges of muscle forces in the erector spinae and obliques. A greater range of force ($p = 0.03$) in residual-side psoas was found during early residual limb swing in people with TTA.

REFERENCES

Acasio, J. C., Shojaei, I., Banerjee, R., Dearth, C. L., Bazrgari, B., & Hendershot, B. D. (2019). Trunk-Pelvis motions and spinal loads during upslope and downslope walking among persons with transfemoral amputation. *Journal of Biomechanics*, *95*, 109316. doi:10.1016/j.jbiomech.2019.109316

Barnett, C. T., Vanicek, N., & Polman, R. C. (2013). Postural responses during volitional and perturbed dynamic balance tasks in new lower limb amputees: A longitudinal study. *Gait & Posture*, *37*(3), 319-25. doi:10.1016/j.gaitpost.2012.07.023

Butowicz, C. M., Dearth, C. L., & Hendershot, B. D. (2019). Joint power distribution does not change within the contralateral limb one year after unilateral limb loss. *Gait & Posture*, *73*, 8-13. doi:10.1016/j.gaitpost.2019.06.011

Castro, M. P., Soares, D., Mendes, E., & Machado, L. (2014). Plantar pressures and ground reaction forces during walking of individuals with unilateral transfemoral amputation. *PM & R: The Journal of Injury, Function, and Rehabilitation*, *6*(8), 698-707. doi:10.1016/j.pmrj.2014.01.019

Childers, W. L., & Kogler, G. F. (2014). Symmetrical kinematics does not imply symmetrical kinetics in people with transtibial amputation using cycling model. *Journal of Rehabilitation Research and Development*, *51*(8), 1243-54. 10.1682/JRRD.2013.11.0241

Darter, B. J., Bastian, A. J., Wolf, E. J., Husson, E. M., Labrecque, B. A., & Hendershot, B. D. (2017). Locomotor adaptability in persons with unilateral transtibial amputation. PloS One, 12(7), e0181120. doi:10.1371/journal.pone.0181120

De Asha, A. R., & Buckley, J. G. (2015a). The effects of laterality on obstacle crossing performance in unilateral trans-tibial amputees. *Clinical Biomechanics, 30*(4), 343-346. doi:10.1016/j.clinbiomech.2015.03.001

De Asha, A. R., & Buckley, J. G. (2015b). The effects of walking speed on minimum toe clearance and on the temporal relationship between minimum clearance and peak swing-foot velocity in unilateral trans-tibial amputees. *Prosthetics and Orthotics International, 39*(2), 120-125. doi:10.1177/0309364613515493

De Asha, A. R., Munjal, R., Kulkarni, J., & Buckley, J. G. (2014). Impact on the biomechanics of overground gait of using an 'Echelon' hydraulic ankle-foot device in unilateral trans-tibial and trans-femoral amputees. *Clinical Biomechanics, 29*(7), 728-734. https://doi.org/10.1016/j.clinbiomech.2014.06.009

Ertl, J. P., Panchbhavi, V., Brackett, W., Ertl, W., & Pritchett, J. (2019). Lower-extremity amputations. *Medscape Drugs & Diseases.* Retrieved from https://emedicine.medscape.com/article/1232102-overview

Fakorede, F. (2018). Increasing awareness this national diabetes month can save limbs and lives. *American Journal of Managed Care*. Retrieved from https://www.ajmc.com/contributor/foluso-fakorede/2018/11/increasing-awareness-this-national-diabetes-month-can-save-limbs-and-lives

Gailey, R., Allen, K., Castles, J., Kucharik, J., & Roeder, M. (2008). Review of secondary physical conditions associated with lower-limb amputation and long-term prosthesis use. *Journal of Rehabilitation Research and Development.* 45. 15-29. 10.1682/JRRD.2006.11.0147.

Giest, T. N., & Chang, Y. H. (2016). Biomechanics of the human walk-to-run gait transition in persons with unilateral transtibial amputation. *Journal of Biomechanics, 49*(9), 1757-1764. doi:10.1016/j.jbiomech.2016.04.004

Golyski, P. R., & Hendershot, B. D. (2018). Trunk and pelvic dynamics during transient turns among individuals with unilateral traumatic lower limb amputation. *Human Movement Science, 58, 41*-54. doi:10.1016/j.humov.2018.01.006

Hendershot, B. D., Bazrgari, B., & Nussbaum, M. A. (2013). Persons with unilateral lower-limb amputation have altered and asymmetric trunk mechanical and neuromuscular behaviors estimated using multidirectional trunk perturbations. *Journal of Biomechanics, 46*(11), 1907-12. doi:10.1016/j.jbiomech.2013.04.018

Hendershot, B. D., & Wolf, E. J. (2015). Persons with unilateral transfemoral amputation have altered lumbosacral kinetics during sitting and standing movements. *Gait & Posture, 42*(2), 204-209. doi:10.1016/j.gaitpost.2015.05.011

Jones, S. F., Twigg, P. C., Scally, A. J., & Buckley, J. G. (2006). The mechanics of landing when stepping down in unilateral lower-limb amputees. *Clinical Biomechanics, 21*(2), 184-193. https://doi.org/10.1016/j.clinbiomech.2005.09.015

Kendell, C., Lemaire, E. D., Kofman, J., & Dudek, N. (2016). Gait adaptations of transfemoral prosthesis users across multiple walking tasks. *Prosthetics and Orthotics International, 40*(1), 89-95. doi:10.1177/0309364614568410

Krupenevich, R. L., Miller, R. H., Hendershot, B. D., Schnall, B. L., & Pruziner, A. L. (2018). Knee adduction moment peak and impulse do not change during the first six months of walking with a prosthesis. *Gait & Posture, 63*, 86-90. doi:10.1016/j.gaitpost.2018.04.040

Lloyd, C. H., Stanhope, S. J., Davis, I. S., & Royer, T. D. (2010). Strength asymmetry and osteoarthritis risk factors in unilateral trans-tibial, amputee gait. *Gait & Posture, 32*(3), 296-300. doi:10.1016/j.gaitpost.2010.05.003

Mahon, C. E., Pruziner, A. L., Hendershot, B. D., Wolf, E. J., Darter, B. J., Foreman, K. B., & Webster, J. B. (2017). Gait and functional outcomes for young, active males with traumatic unilateral transfemoral limb loss. *Military Medicine, 182*(7), 1913-1923. doi:10.7205/MILMED-D-16-00356

Mayer, A., Tihanyi, J., Bretz, K., Csende, Z., Bretz, E., & Horvath, M. (2011). Adaptation to altered balance conditions in unilateral amputees due to atherosclerosis: a randomized controlled study. *BMC Musculoskeletal Disorders, 12*, 118. doi:10.1186/1471-2474-12-118

Moher, D., Liberati, A., Telzlaff, J., & Altman, D. G. (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(7): e1000097. doi:10.1371/journal.pmed.1000097

Molina-Rueda, F., Alguacil-Diego, I. M., Molero, Sánchez, A., Carratala-Tejada, M., Rivas Montero, F. M., & Miangolarra-Page, J. C. (2013). Knee and hip internal moments and upper-body kinematics in the frontal plane in unilateral transtibial amputees. *Gait & Posture, 37*(3), 436-439. doi:10.1016/j.gaitpost.2012.08.019

Molina-Rueda, F., Molero-Sánchez, A., Alguacil-Diego, I. M., Carratala-Tejada, M., Cuesta-Gomez, A., & Miangolarra-Page, J. C. (2016). Weight symmetry and latency scores for unexpected surface perturbations in subjects with traumatic and vascular unilateral transtibial amputation. *PM & R: The Journal of Injury, Function, and Rehabilitation, 8*(3), 235-40. doi:10.1016/j.pmrj.2015.05.024

Morgenroth, D. C., Roland, M., Pruziner, A. L., & Czerniecki, J. M. (2018). Transfemoral amputee intact limb loading and compensatory gait mechanics during down slope ambulation and the effect of prosthetic knee mechanisms. *Clinical Biomechanics (Bristol, Avon), 55*, 65-72. doi:10.1016/j.clinbiomech.2018.04.007

Murray, A. M., Gaffney, B. M., Davidson, B. S., & Christiansen, C. L. (2017). Biomechanical compensations of the trunk and lower extremities during stepping tasks after unilateral transtibial amputation. *Clinical Biomechanics (Bristol, Avon), 49,* 64-71. doi:10.1016/j.clinbiomech.2017.08.010

National Institutes of Health (2014). Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies. Available online at: https://www.nhlbi.nih.gov/health-pro/guidelines/in-develop/cardiovascular-risk-reduction/tools/cohort

Pruziner, A. L., Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Miller, M. W., Wolf, E. J., Hatfield, B. D., Dearth, C. L., & Gentili, R. J. (2019). Biomechanical and neurocognitive performance outcomes of walking with transtibial limb loss while challenged by a concurrent task. *Experimental Brain Research, 237*(2), 477-491. doi:10.1007/s00221-018-5419-8

Pruziner, A. L., Werner, K. M., Copple, T. J., Hendershot, B. D., & Wolf, E. J. (2014). Does intact limb loading differ in servicemembers with traumatic lower limb loss? *Clinical Orthopaedics and Related Research, 724*(10), 3068-75. doi:10.1007/s11999-014-3663-1

Rodrigues, F. B., Andrade, A. O., & Vieira, M. F. (2019). Effects of inclined surfaces on gait variability and stability in unilateral lower limb amputees. *Medical & Biological Engineering & Computing.* doi:10.1007/s11517-019-02042-6

Russell, E., & Wilken, J. M. (2014). Biomechanical risk factors for knee osteoarthritis when using passive and powered ankle-foot prostheses. *Clinical Biomechanics (Bristol, Avon), 29*(10), 1186-92. doi:10.1016/j.clinbiomech.2014.09.005

Sanderson, M., & Martin, P. (1997). October. Lower extremity kinematic and kinetic adaptations in unilateral below-knee amputees during walking. *Gait & Posture, 6(*2), 126-136. doi:10.1016/S0966-6362(97)01112-0

Schnall, B. L., Hendershot, B. D., Bell, J. C., & Wolf, E. J. (2014). Kinematic analysis of males with transtibial amputation carrying military loads. *Journal of Rehabilitation Research and Development, 51*(10), 1505-14. doi:10.1682/JRRD.2014.01.0022

Schoeman, M., Diss, C. E., & Strike, S. C. (2013). Asymmetrical loading demands associated with vertical jump landings in people with unilateral transtibial amputation. *Journal of Rehabilitation Research and Development, 50*(10), 1435-47. doi:10.1682/JRRD.2012.10.0199

Selgrade, B. P., Toney, M. E., & Chang, Y. H. (2017). Two biomechanical strategies for locomotor adaptation to split-belt treadmill walking in subjects with and without transtibial amputation. *Journal of Biomechanics, 53,* 136-143. doi:10.1016/j.jbiomech.2017.01.012

Shojaei, I., Hendershot, B. D., Acasio, J. C., Dearth, C. L., Ballard, M., & Bazrgari, B. (2019). Trunk muscle forces and spinal loads in persons with unilateral transfemoral amputation during sit-to-stand and stand-to-sit activities. *Clinical Biomechanics (Bristol, Avon), 63*, 95-103. doi:10.1016/j.clinbiomech.2019.02.021

Shojaei, I., Hendershot, B. D., Wolf, E. J., & Bazrgari, B. (2016). Persons with unilateral transfemoral amputation experience larger spinal loads during level-ground walking compared to able-bodied individuals. *Clinical Biomechanics (Bristol, Avon), 32*, 157-163. doi:10.1016/j.clinbiomech.2015.11.018

Silverman, A. K., & Neptune, R. R. (2014). Three-dimensional knee joint contact forces during walking in unilateral transtibial amputees. *Journal of Biomechanics*, *47*(11), 2556-62. doi:10.1016/j.jbiomech.2014.06.006

Standard of Care: Lower Extremity Amputation. (2011). Brigham and Women's Hospital Department of Rehabilitation Services. Retrieved from https://www.brighamandwomens.org/assets/BWH/patients-and-families/rehabilitation-services/pdfs/general-le-amputation-bwh.pdf

Struyf, P. A., Heugten, C. M. V., Hitters, M. W., & Smeets, R. J. (2009). The prevalence of osteoarthritis of the intact hip and knee among traumatic leg amputees. *Archives of Physical Medicine and Rehabilitation*, *90*(3), 440–446. doi: 10.1016/j.apmr.2008.08.220

Veritas Health Innovation. (2019). Covidence systematic review software. Melbourne, Australia. Available at www.covidence.org

Winter, D., & Sienko, S. (1988). Biomechanics of below-knee amputee gait. *Journal of Biomechanics, 21*(5), 361-367. https://doi.org/10.1016/0021-9290(88)90142-X

Yoder, A. J., Petrella, A. J., & Silverman, A. K. (2015). Trunk-pelvis motion, joint loads, and muscle forces during walking with a transtibial amputation. *Gait & Posture, 41*(3), 757-62. doi:10.1016/j.gaitpost.2015.01.016