Abstract

Research addressing lower limb amputee gait and prosthetic design often focuses on men, despite female lower limb amputees having different risk factors and lower success with their prosthetics overall. It is widely agreed that sex differences exist in able-bodied gait, but research analyzing sex differences in amputee gait is rare. This study compared male and female transtibial amputee gait to ascertain potential sex differences. Forty-five transtibial amputees were asked to walk at their self-selected speed and spatiotemporal gait data were obtained. Both the mean and variability metric of parameters were analyzed for 10 male and 10 female participants. Within sexes, amputated limbs had a shorter stance time, longer swing time, and larger step length. Females had a 10% shorter stance time and 26% larger normalized step and stride length than males. Female participants also walked over 20% faster than male participants. Finally, significant interactions were found in the mean and variability metric of stride velocity, indicating greater variability in women. These findings suggest that sex differences exist in transtibial amputee gait, offering possible explanations for the different comorbidities experienced by female lower limb amputees. These results have major implications for female amputees and for sex-specific research, rehabilitation, and prosthetic design.

Keywords: sex-based research, female amputees, gait analysis, variability, prosthetic

Word Count: 3,489 words

Introduction

Lower limb amputees (LLAs) suffer from various comorbidities, including a higher incidence and risk of osteoarthritis (OA) in their intact limb as compared to age-matched non-amputees.[1,2] Gait assessments of LLAs are often used to evaluate risk of comorbidities and assess aspects of prosthetic limb design.[1–4] While there is a great deal of research assessing gait in LLAs, the majority of the subject base is male amputee dominated.[1–4] This may be due to the fact that the majority (~70%) of LLAs in the U.S., Canada, and Australia are male.[5–7] However, it may not be appropriate to apply research findings from male LLAs to the female LLA population, as able-bodied (AB) women have a 2-3x higher risk of developing knee OA than AB males.[8] Furthermore, female LLAs experience a host of differing comorbidities compared to their male counterparts, including heightened risk of OA (15% per kg/m^2), greater pain and lower functional abilities with their prosthetics, and they are ~6x more likely to experience a fall-related injury.[5,9–12] This information brings into question what sex differences are contributing to the different comorbidities associated with female LLAs. As both the incidence of OA as well as falls have been associated with abnormalities in gait (e.g., asymmetry),[8,9] a clear starting point would be to consider potential sex-based differences in gait.

In the AB population, it is well documented that men and women differ in spatiotemporal and kinematic gait parameters.[8,13–16] Consistent differences in hip and ankle range of motion have been found and are believed to influence injury mechanisms in AB women.[13,14,16] Sex differences in AB gait are often attributed to differences in gait control strategy, anatomy and muscular strength.[13,15] However, despite these known differences in the AB population, greater prevalence of comorbidities in female LLAs, and the large population of female LLAs (~30% in the U.S., Canada, and Australia),[5–7] there is very little research examining the biomechanics of female LLA gait as well as if and how they differ from their male counterparts.

Sex-based research in general has shown to improve a large variety of medical science and engineering outcomes.[17] Thus, understanding sex differences in LLA gait not only has major implications in prosthetic design and rehabilitation, but also in science and engineering research as a whole. This presents a clear need to explore sex differences in LLA gait. Therefore, the purpose of this descriptive study was to ascertain sex differences in transtibial amputee (TTA) gait through the comparison of male and female TTA spatiotemporal gait parameters.

Methods

Anonymized gait data were obtained from a previously published study that included a cohort of 45 unilateral TTAs (35 men, 78%; mean ± standard deviation (SD): age = 61 ± 14 years; height = 175 ± 10.0 cm; weight = 91.2 ± 19.1 kg; time since amputation = 16 ± 19 years) with well-fitting prostheses as judged by the participant's prosthetist.[18] A subsample of 10 male participants was randomly selected from the 35 to have an equal sample size between groups for statistical analyses. The characteristics of these 20 participants (10 men, 50%; mean ± SD: age = 59 ± 16 years; height = 171 ± 12.0 cm; weight = 89.6 ± 20.7 kg; time since amputation = 15 ± 18 years) are given in Table 1. Ethics for the original study was approved by the XXXX Clinical Human Research Ethics Committee with all participants providing written consent. For use of the anonymized data in this study, further ethics approval was obtained by the XXXX Human Research Ethics Board.

The data obtained were non-normalized spatiotemporal parameters, including gait velocity, stride velocity, stance time, swing time, step length, stride length, and step time (Table 2). All parameters, with the exception of gait velocity, were measured for both the amputated limb (AL) and non-amputated limb (NAL) across 10 walking trials. Gait velocity was still measured across 10 trials but not for both limbs because it is a parameter of the body center and thus combined for both limbs. The raw data shared from the previous study were participant characteristics and mean parameter values for each limb (when available) at each trial. In the previous study, gait data were obtained in a rehabilitation center using an instrumented GAITRite walkway system (CIR Systems Inc., Sparta, NJ, USA) that captures footfalls at a sampling rate of 120 Hz across an area of 4.9 m x 0.6 m.[18] Participants were asked to walk at their self-selected speed across the GAITRite mat for 10 consecutive trials, starting and stopping 2 m before and after the walkway end.[18]

Scaling factors were used to normalize gait data by leg length (Table 2).[19] However, only height was measured in the previous study and not intact leg length, a more common normalization parameter.[19] Therefore, separate anthropometric scaling factors were used to determine leg length of participants based on their height.[20,21] Statistical analyses were run on both the normalized (non-dimensional) and non-normalized gait parameters. These analyses are described as follows. Normality of all parameters was confirmed using Shapiro-Wilk tests. The current study's statistical design was developed to explore the effect of sex on spatiotemporal gait parameters while considering potential interactions between sex, limb status, and trial number. Assessing parameter means and variabilities across trials, rather than averaged over trials, provides a more comprehensive investigation of participant gait and its variation trial-to-trial. Therefore, we were interested in analyzing sex differences in both gait parameter means and gait parameter variabilities across trials and across limbs. To do so, two separate statistical tests were run. First, three-way mixed ANOVAs were run separately for the means and variability metrics (VMs) of all gait parameters except gait velocity. In these tests, sex was the between subject's factor, split into two levels (male, female). The two within subject's factors were trial number, split into seven levels (trials 4-10), and limb status, split into two levels (AL, NAL). Only trials 4-10 were analyzed as the first three trials demonstrated acclimatization effects (i.e., subjects were still adjusting to gait analysis) and were thus considered practice trials. VM parameters for each limb were calculated by subtracting the mean value of each trial by the average over the seven trials. For example, to determine the VM of the amputated limb's stride velocity for trial 4, the following calculation was performed:

$$strideV_{AL\ t4_{VM}} = strideV_{AL\ t4_{mean}} - avg(strideV_{AL\ t4_{mean}} : strideV_{AL\ t10_{mean}}) \tag{1}$$

As can be seen in the above equation, the VM data for a given parameter at a given trial is a form of residual showing the difference of that data from the subject's own mean. However, when considered across all trials, these VM data do indeed demonstrate the subject's gait variability for that parameter. For example, if the VM of a parameter at every trial were zero, this would mean there is no variability in that parameter across trials. Second, two-way mixed ANOVAs were run separately for the mean and VM of gait velocity. In these tests, sex was the between subject's factor, split into two levels (male, female) and the within subject's factor was trial number, split into seven levels (trials 4-10). VMs were calculated the same way as previously described. The need for a different statistical test for this parameter was because gait velocity was not measured for each limb, therefore a within-subject's factor of limb could not be analyzed.

To assess demographic similarity between the male and female cohorts, characteristics including age, stump length, height, weight, intact leg length, BMI, and time since amputation were analyzed using independent-samples t-tests to determine if significant sex differences existed.

To further interpret results, Bonferroni corrected post-hoc tests were conducted when statistically significant interactions were found. All analyses were performed in SPSS (version 26.0, IBM Corp., Armonk, NY, USA) and significance was determined based on $p < .05$.

Results

Regarding participant characteristics, male participants were significantly taller (179 ± 10.7 cm compared with 162 ± 6.64 cm, $p < .001$) and heavier (99.6 ± 18.9 kg compared with 79.6 ± 19.2 kg, $p = .031$) than female participants. Male participants also had a significantly longer intact leg length than females (94.9 ± 5.66 cm compared with 84.9 ± 3.48 cm, $p < .001$). No significant difference between sexes was found for participant BMI ($p = .754$), age ($p = .338$), stump length ($p = .139$), or time since amputation ($p = .308$) (Table 1).

Considering gait parameter means and VMs, statistical findings for normalized (i.e., non-dimensional) and non-normalized parameters were very similar. For any statistically significant results found in both normalized and non-normalized variables, p-values are given for both. Otherwise, differences in significant results are clearly noted. Only significant results demonstrating a main effect of sex are shown in figures since sex differences were the main interest of this exploratory study. If a significant main effect of sex was present for a variable when normalized and non-normalized, figures are only given for the non-normalized case to ease comprehension.

For gait parameter means, stride velocity demonstrated a statistically significant three-way interaction between limb*trial*sex (normalized: $p = .008$; non-normalized: $p = .004$) (Figure 1A). Through post-hoc analysis, a significant simple two-way interaction was found between trial*limb for females (normalized: $p = .045$; non-normalized: $p = .044$). However, Bonferroni corrected post-hoc tests did not demonstrate further statistically significant simple main effects of limb or trial on stride velocity for females. There were no other statistically significant interactions. However, statistically significant main effects of both limb and sex were found for parameter means. For all participants, a statistically significant main effect of limb was found on stance time (Figure 2), swing time, and step length (Figure 3A), with ALs having a shorter stance time (normalized: 2.31 ± 0.271 compared with 2.43 ± 0.258, $p < .001$; non-normalized: 0.693 ± 0.079 s compared with 0.730 ± 0.077 s, $p < .001$), longer swing time (normalized: 1.34 ± 0.126 compared with 1.22 ± 0.121, $p < .001$; non-normalized: 0.409 ± 0.037 s compared with 0.372 ± 0.033 s, $p < .001$), and larger step length (normalized: 0.728 ± 0.176 compared with 0.693 ± 0.156, $p = .026$; non-normalized: 66.0 ± 13.2 cm compared with 63.1 ± 12.4 cm, $p = .020$). A statistically significant main effect of sex was found on stride velocity (Figure 1A) and gait velocity (Figure 1B), with females having a higher stride velocity (normalized: 0.452 ± 0.086 compared with 0.340 ± 0.082, $p = 0.008$; non-normalized: 130 ± 24.8 cm/s compared with 103 ± 22.4 cm/s, $p = 0.019$) and a higher gait velocity (normalized: 0.450 ± 0.087 compared with 0.339 ± 0.083, $p = 0.009$; non-normalized: 130 ± 25.1 cm/s compared with 103 ± 22.5 cm/s, $p = 0.020$). As well, females had a significantly shorter non-normalized stance time than men (0.679 ± 0.067 s compared with 0.747 ± 0.074 s, $p = .002$) (Figure 2). To note, this result was not significant for normalized stance time ($p = .065$). Finally, compared with male participants, females had a significantly longer normalized step length (0.811 ± 0.143 compared with 0.598 ± 0.102, $p = .002$) and normalized stride length (1.63 ± 0.285 compared with 1.20 ± 0.202, $p = .002$), see Figure 3A and Figure 3B respectively. However, these results were not significant for non-normalized step length ($p = .137$) or stride length ($p = .676$).

For gait parameter VMs, the stride velocity VM demonstrated a significant three-way interaction between limb*trial*sex (normalized: *p* = .015; non-normalized: *p* = .014) (Figure 4). Through post-hoc analysis, a significant simple two-way interaction was found between trial*limb for females (normalized: *p* = .045; non-normalized: *p* = .044). Bonferroni corrected post-hoc tests demonstrated a statistically significant simple main effect of limb on stride velocity VM for females at trial 6 (normalized: AL: -0.00261 ± 0.00602 as compared to NAL: 0.00206 ± 0.00938, *p* = .041; non-normalized: AL: -0.761 ± 1.74 cm/s as compared to NAL: 0.593 ± 2.70 cm/s, *p* = .040). As well, a statistically significant two-way interaction between trial*sex was found for step length VM (normalized: *p* = .036; non-normalized: *p* = .033). However, Bonferroni corrected post-hoc tests failed to demonstrate statistically significant simple main effects of trial or sex on step length.

Discussion

The purpose of this study was to analyze TTA gait parameters and ascertain potential sex differences. With this objective in mind, there were three major findings. First, male and female TTAs had common spatiotemporal gait differences between AL and NAL, with a shorter stance time, longer swing time, and larger step length in their AL. This supports common kinematic differences seen in literature as a result of prosthetic use.[22–24] Although not new, the consistency of this finding with other studies helps to confirm the validity of our results. Second, female TTAs had a significantly higher gait and stride velocity, possibly achieved by their larger normalized stride and step length or by their shorter non-normalized stance time. As many injury, fall-risk, and other comorbidities are related to gait velocity,[22,25] this result may help explain why female TTAs have higher rates of these complications. Third, females demonstrated higher variability in stride velocity through parameter mean and VM interactions. High variability in gait parameters may contribute to fall-risk and future mobility impairments,[26–28] suggesting these results offer important female TTA rehabilitation considerations. Taken together, these results suggest that while differences in AL and NAL gait parameters occur across both sexes, greater gait velocity and variability in female TTAs may necessitate female LLA-specific research. The following paragraphs further discuss potential implications of the three main findings.

As the first main finding, ALs were found to have a shorter stance time (Figure 2), longer swing time, and larger step length (Figure 3A) across both sexes. Such differences were significant when analyzing normalized or non-normalized gait parameters. These results align with the current understanding of compensatory mechanisms in amputee gait, helping to confirm the validity of our findings.[3,22–24] More specifically, a shorter stance time on ALs indicates an amputee's distrust or the discomfort experienced when loading their prosthetic limb.[22] Therefore, amputees will shorten the time they spend on their AL to mitigate these concerns. Limb strength asymmetries are also believed to contribute to a greater reliance on their intact limb for compensation.[3] A longer AL swing time is believed to allude to variations between the AL and NAL in inertial and mass properties.[22] The AL's larger step length is thought to relate to compensating for poor push-off power from the prosthetic limb.[23,24]

The second major finding in this study was the higher stride and gait velocity seen in females (Figure 1A and Figure 1B). It is acknowledged that velocity results are likely correlated to those of other spatiotemporal parameters like stride length and step length or stance time. Sex differences in these parameters may provide insights into female versus male LLA gait strategies. For normalized parameters, it was found that in spite of their smaller stature, females took significantly larger steps and strides than males (Figure 3A and Figure 3B). Therefore, it can be postulated that females achieved their greater velocity by taking larger steps or strides. Considering non-normalized parameters, the faster velocity observed in females may have also been achieved in part by their statistically shorter stance time (Figure 2). Conversely, no difference is typically found in gait speed of AB men and women, where AB women are found to increase their cadence to achieve similar speeds as men.[13,15] Together, these findings provide new insights to how female LLAs mobilize compared to males. Greater walking speed has been associated with a higher Medicare Functional Classification Level (K-level), which is a system commonly used to describe walking potential in LLAs.[29] Despite this link suggesting successful mobility,[29] this result has further implications for female amputee health as increased walking speed potentially presents a greater fall-risk as well as OA in amputees.[25] Increased fall-risk has been linked with minimum toe clearance (MTC) during forward swing, as it is the point where an individual's toes are closest to the ground.[25] MTC increases with faster walking speed in AB individuals, thus no increased fall-risk is presented.[25] However, a study found MTC is actually reduced on the AL of TTAs in general and does not increase with increased speeds.[25] Therefore, TTAs may be presented with an increased risk of falls at faster walking speeds.[25] Considering this relation between fall-risk and walking speed, this study's finding of greater gait and stride velocity in females offers a possible explanation for their increased fall-risk as well as suggests a potential need for female LLA-specific rehabilitation and prosthetic design. Regarding rehabilitation, females could be cautioned on walking speed, however, reducing walking speed below one's preferred pace has shown to increase energetic cost.[30] Alternatively, designing a female prosthetic foot that dorsiflexes during forward swing could reduce fall-risk as such designs have shown to increase MTC.[31,32]

Studies have also shown that faster walking speeds in LLAs increases both vertical ground reaction force (vGRF) and loading asymmetry, hypothesized to be from improper prosthetic inertial properties and asymmetric placement of their center of gravity.[22] Both increased intact limb vGRF and loading asymmetries are linked to knee pain and risk of OA in LLAs.[1–3,22] From this relation between walking speed and risk of OA, this study's result of increased gait and stride velocity in females presents implications for their health and quality of life. This link may provide an explanation for the heightened risk of OA seen in female LLAs and indicate a need for sex-specific prosthetics. More specifically, foot stiffness parameters in female prosthetics could be altered to potentially reduce intact limb vGRF since such parameters have been shown to impact intact limb loading as well as metabolic cost of gait.[33]

Overall, the suggestion that a higher walking speed indicates greater mobility potential in LLAs does not negate its links to comorbidities seen in females, including increased risk of falls as well as OA. Future research needs to consider the implications these links have for females and how they may suggest a need for sex-specific rehabilitation and prosthetic design.

The third major finding was the statistically significant interactions between limb*trial*sex for the mean and VM of stride velocity. These interactions demonstrate greater trial-to-trial variability in female participants (Figure 4). In male participants, parameter values remained more consistent across trials and limbs while in females, parameter values varied greatly across trials and limbs. In AB individuals, some gait variability and fluctuations are expected and not cause for concern.[28] However, increased gait variability has been associated with greater fall-risk as well as being a predictor for future mobility impairments.[26–28] Gait variability is often viewed as the neuromuscular control system's inability to consistently maintain a steady gait pattern, resulting in instability and higher fall-risk.[28] Due to this link between fall-risk and gait variability, this study's finding presents potential major ramifications for female LLAs and their rehabilitation, offering a possible explanation for their greater risk of falls.

Limitations of this study include only involving TTAs, therefore the results do not extend over all LLAs. However, transtibial amputation level is common in LLAs,[6,7] and is a reasonable starting point to assess sex differences without introducing confounding factors like amputation level. As well, further information regarding participant prosthesis type or componentry could help reinforce arguments regarding female LLA gait strategy and the potential links to their increased risk factors. Despite the above limitations, the available data and research on female amputees is lacking. Therefore, it is believed these data provide a useful initial and exploratory attempt to understand and determine sex differences in LLAs.

The findings of this study offer preliminary information and insight into TTA sex differences, potentially linking them to female comorbidities. These findings present implications for female LLAs in the context of rehabilitation and prosthetic design. However, further research is needed to better understand the implications of sex differences and how they can guide sex-specific rehabilitation protocols and prosthetics. For example, research addressing how prosthetic mass and stiffness properties can be optimized for women may give such insight into improving their success with artificial limbs. As well, future work assessing sex differences in gait and joint kinematics is needed to analyze their correspondence to the spatiotemporal sex differences found here. As well, insight into female joint kinematics is needed for sex-specific prosthesis development. In general, future research may indicate that sex-specific rehabilitation and prosthetics are necessary to improve the outcomes and attempt to address the various comorbidities of female LLAs.

To summarize, this study is the first to our knowledge to analyze sex differences in TTA gait. A number of differences were found between sexes, including females having a shorter stance time, greater normalized step and stride length, and faster gait and stride velocity. As well, females had a greater stride velocity variability compared to males. Results from this study have been associated with comorbidities present in female LLAs. Further research into the biomechanics of female LLA gait is needed to corroborate the sex differences found and to help understand the needs of female LLAs for rehabilitation and prosthetic design.

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Tables

Table 1 Characteristics of the 10 male and 10 female TTA participants.

Characteristic	Female (mean ± SD)	Male (mean ± SD)	*p*-Value
Age (years)	63 ± 21	56 ± 10	.338
Stump length (cm)	17.1 ± 2.34	15.2 ± 3.09	.139
Time since amputation (years)	13 ± 21	17 ± 17	.308
Height (cm)	162 ± 6.64	179 ± 10.7	< .001*
Weight (kg)	79.6 ± 19.2	99.6 ± 18.9	.031*
BMI (kg/m^2)	30.3 ± 6.83	31.2 ± 6.11	.754
Intact leg length (cm)	84.9 ± 3.48	94.9 ± 5.66	< .001*
Amputation pathology (%)			
Peripheral vascular	40.0	30	-
Trauma	20.0	50	-
Other	40.0	20	-

Abbreviations: SD, standard deviation; TTA, transtibial amputee. * Denotes significant *p*-values.

Table 2 Gait parameter means and SDs for the 10 male and 10 female participants.

(A) Non-normalized gait parameter	Female (mean ± SD)	Male (mean ± SD)
Gait velocity (cm/s)	129.9 ± 25.1	102.8 ± 22.5
Stance time (s)		
AL	0.660 ± 0.066	0.728 ± 0.080
NAL	0.697 ± 0.070	0.767 ± 0.069
Swing time (s)		
AL	0.402 ± 0.030	0.416 ± 0.045
NAL	0.367 ± 0.031	0.377 ± 0.037
Stride velocity (cm/s)		
AL	130.4 ± 24.5	103.1 ± 22.5
NAL	130.4 ± 25.0	103.3 ± 22.3
Stride length (cm)		
AL	137.8 ± 23.2	120.8 ± 24.8
NAL	137.7 ± 23.2	121.2 ± 24.9
Step time (s)		
AL	0.538 ± 0.039	0.581 ± 0.056
NAL	0.522 ± 0.011	0.566 ± 0.055
Step length (cm)		
AL	70.8 ± 12.0	61.2 ± 13.2
NAL	66.8 ± 11.8	59.5 ± 12.4

(B) Non-dimensional gait parameter	Female (mean ± SD)	Male (mean ± SD)
Gait velocity	0.450 ± 0.087	0.339 ± 0.083
Stance time		
AL	2.19 ± 0.149	2.42 ± 0.318
NAL	2.32 ± 0.186	2.53 ± 0.279
Swing time		
AL	1.34 ± 0.077	1.35 ± 0.166
NAL	1.22 ± 0.101	1.22 ± 0.143
Stride velocity		
AL	0.452 ± 0.085	0.340 ± 0.083
NAL	0.452 ± 0.087	0.340 ± 0.082
Stride length		
AL	1.63 ± 0.285	1.20 ± 0.199
NAL	1.62 ± 0.285	1.20 ± 0.204
Step time		
AL	1.83 ± 0.149	1.93 ± 0.259
NAL	1.77 ± 0.052	1.88 ± 0.245
Step length		
AL	0.835 ± 0.153	0.608 ± 0.113
NAL	0.787 ± 0.139	0.589 ± 0.100

Abbreviations: SD, standard deviation; AL, amputated limb; NAL, non-amputated limb.

Figure Captions

Figure 1 – (A) Male and Female Stride Velocity Mean Interaction Graph. This graph demonstrates the statistically significant three-way interaction of limb*trial*sex on stride velocity for men and women. It also demonstrates the statistically significant main effect of sex on stride velocity. Although small, error bars are present and indicate the standard error. (B) Male and Female Gait Velocity Mean Interaction Graph. This graph demonstrates the two-way interaction of trial*sex on gait velocity for men and women. It also demonstrates the statistically significant main effect of sex on gait velocity. Although small, error bars are present and indicate the standard error.

Figure 2 – Male and Female Stance Time Mean Interaction Graph. This graph demonstrates the three-way interaction of limb*trial*sex on stance time for men and women. It also demonstrates the statistically significant main effect of limb and of sex on stance time. Although small, error bars are present and indicate the standard error.

Figure 3 – (A) Male and Female Normalized Step Length Mean Interaction Graph. This graph demonstrates the three-way interaction of limb*trial*sex on normalized step length for men and women. It also demonstrates the statistically significant main effect of limb and of sex on normalized step length. Although small, error bars are present and indicate the standard error. (B) Male and Female Normalized Stride Length Mean Interaction Graph. This graph demonstrates the three-way interaction of limb*trial*sex on normalized stride length for men and women. It also demonstrates the statistically significant main effect of sex on normalized stride length. Although small, error bars are present and indicate the standard error.

Figure 4 – Male and Female Stride Velocity Variability Metric Interaction Graph. This graph demonstrates the statistically significant three-way interaction of limb*trial*sex on stride velocity variability metric for men (A) and women (B). The asterisks indicates at which trial the post-hoc tests found the statistically significant simple main effect of limb. Error bars indicate the standard error.