Gait & Posture 98 (2022) 1–5

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

The effect of sex, stature, and limb length on the preferred walk-to-run transition speed

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ARTICLE INFO

Keywords:
Walk-to-run
Transition
Stature
Limb length
Sex-differences

ABSTRACT

Background: The *preferred* walk-to-run transition speed (PTS) for healthy adults is approximately 2 m•s^{-1}, however, PTS is influenced by anthropometric factors. Yet despite known sex differences in anthropometrics, studies have reported no sex differences in PTS.
Research question: Do stature and limb length affect PTS in the same way for both male and female healthy adults?
Methods: Thirty-seven (19 female) non-injured adults volunteered for this study. Participants completed a walk-to-run transition protocol, where the treadmill speed was increased from 1.2 m•s^{-1} to 2.2 m•s^{-1}, in increments of 0.1 m•s^{-1} every two minutes. An independent t-test compared PTS between sexes. Multiple regression analysis determined the effect of sex and stature and sex and limb length on PTS.
Results: Female participants transitioned at a lower PTS than male participants (1.8 (0.2) m•s^{-1} versus 1.9 (0.1) m•s^{-1}; $p \leq 0.026$). Sex and stature explained 19% of the variance in PTS, while sex and limb length explained 21% of the variance. Including interactions increased the variance explained by 23% and 2% for sex and stature and sex and limb length, respectively. The significant interaction between sex and stature showed PTS was inversely proportional to stature for male participants but directly proportional for female participants.
Significance: These findings suggest that the extent to which stature and limb length influence the preferred transition speed may differ between sexes.

1. Introduction

Adult humans alternate between walking and running gait patterns when moving on land, depending on the speed. The *preferred* transition speed (PTS) is defined as the speed at which an individual spontaneously transitions from a walking gait pattern to a running gait pattern or vice versa. Understanding PTS is important for individuals who walk at speeds close to PTS, such as those in occupations where group locomotion, i.e. marching and parading, or timed fitness tests may be required [1]; or in racewalkers [2]. Ambulating at speeds close to PTS is associated with greater movement variability [3], increased rate of perceived effort [4,5], and increased muscle activity [5,6], which potentially increases an individual's injury risk. Furthermore, female athletes [7] and female military personnel [8,9] are at an increased risk of injury than their male counterparts, and so better understanding sex differences in PTS may help better understand sex differences in injury risk during exercise.

Research studies have used a variety of methods to determine PTS. These methods include incremental treadmill protocols, where participants dismounted the treadmill between speeds [4,6,10–17], or continuous treadmill protocols with various levels of constant acceleration [3,13,18] or continuous-stepwise treadmill protocols where the speed was increased in steps with a steady-state period at each speed [19–21]. Some studies even used overground protocols where participants were asked to use constant acceleration [22] or spontaneously transition from a walking gait to a running gait [23]. A limitation of

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https://doi.org/10.1016/j.gaitpost.2022.08.006
Received 22 July 2021; Received in revised form 5 August 2022; Accepted 11 August 2022
Available online 13 August 2022

incremental protocols is that no true gait transition occurs, whereas with the constantly accelerating protocols a true gait transition occurs, but the accurate determination of PTS is difficult as there is no 'decision period'. Therefore, the continuous-stepwise protocol seems the most appropriate to use, as it allows for both a true transition and a 'decision period' for accurate determination of PTS.

PTS is said to be approximately 2 $m{\bullet}s^{-1}$ for non-injured adults [5,22,24], however, studies have reported a mean PTS between 2.05 and 2.26 $m{\bullet}s^{-1}$ for male participants [12,16,20] and between 1.99 and 2.04 $m{\bullet}s^{-1}$ for female participants [12,16,17]. Despite extensive research, the triggering mechanism for transitioning between walking and running is still not fully understood [24,25]. PTS is believed to be influenced by many factors, including metabolic factors [4,5,15,17,26] where reductions in muscle activity and changes in motor unit recruitment contribute to PTS more than whole-body energy expenditure; biomechanical factors [14,19,21,27] where loading rates and ankle dorsiflexor and hip extensor moments and powers influence PTS; and anthropometric factors [12,16,20,21] where longitudinal body dimensions (i.e. stature, limb length, thigh length, shank length) are correlated (both positively and negatively) with PTS and transverse body dimensions (i.e. calf girth, thigh girth, bitrochanteric diameter, bicristal diameter) are negatively correlated with PTS.

The direction and strength of the relationships between anthropometric measures and PTS vary between studies [12,16,20,21] with reports showing an association between anthropometric dimensions [12,20] and segmental body proportions [20] and PTS, and that sex differences in body size should be considered when interpreting PTS [16]. Variability in correlation coefficients between studies may be due to differences in protocols used, sample sizes (impacting subsequent precision of the estimate), and/or the populations sampled. The most robust correlation coefficient between PTS and stature for both male ($n = 59$) and female participants ($n = 27$) is positive ($r = 0.01$, $p > 0.05$, and 95% CI=−0.25 0.27 and $r = 0.28$, $p > 0.05$, and 95% CI=−0.11 0.60). On the other hand, the most robust correlation coefficient between PTS and limb length for male participants ($n = 59$) is negative ($r = -0.31$, $p < 0.05$, and 95% CI=−0.58 −0.06; though all other studies report positive coefficients); whereas, for female participants ($n = 27$), the most robust correlation coefficient between PTS and limb length is positive ($r = 0.20$, $p > 0.05$, and 95% CI=−0.19 0.54). These data suggest that there may be a sex specific effect of stature, and limb length, on PTS. However, published literature has reported no significant sex differences in PTS [4,10–12,16], which does not seem to align with known sex differences in anthropometrics and strength.

Given known sex differences in anthropometrics, and the inconsistencies of relationships between anthropometrics and PTS in published literature, this study aimed to determine if stature and limb length affect PTS in the same way for both male and female non-injured adults. We hypothesised that there would be no sex significant differences in PTS and that there would be similar relationships between both stature and limb length and PTS. We hypothesised that sex would not affect these relationships.

2. Methods

Thirty-seven (19 female) participants were recruited from University staff, student, and visitor population. Participants were aerobically active, healthy, and free from lower limb musculoskeletal injuries for at least 90 days before participation. This study was approved by the Ministry of Defence Research Ethics Committee (Ref: 888/MODREC/18) and the University of Salford Ethics Committee (Ref: HSR1718–123). Participants signed an informed consent form before participation.

The sample size was dictated by time and resource constraints [28]. However, this is in line with previous studies with sample sizes ranging from 18 to 59 [12,16,20,21]; including sex-specific analysis of 15–27 female participants [12,16] and/or 11–59 male participants [12,16,20].

Stature (m) was measured using a stadiometer with participants barefoot. Body mass (kg) was measured using standard scales. Lower limb length (m), defined as the distance from the anterior superior iliac spines (ASIS) to the medial malleoli (MMAL), was measured while participants lay supine.

Participants completed a continuous stepwise walk-to-run transition protocol using the C-Mill instrumented treadmill (Motek Medical, The Netherlands) while wearing standardised footwear (MAGNUM, Hi-Tec Sports International Holdings BV, The Netherlands). All participants were familiar with treadmill walking and running and could familiarise themselves before testing. The testing protocol was programmed into the CueFors software (Motek Medical, The Netherlands) and the experimenter controlled the computer. The program began at a treadmill speed of 1.2 $m{\bullet}s^{-1}$ and the speed was incrementally increased (0.1 $m{\bullet}s^{-1}$) every two minutes until a final speed of 2.2 $m{\bullet}s^{-1}$. Participants were asked to *"walk on the treadmill until they felt it would be more comfortable to run and then transition into a run"*. PTS was identified through visual inspection and defined as the first speed at which participants consistently adopted a running gait pattern - a gait pattern with two aerial phases in each gait cycle.

Unless otherwise stated, SPSS (IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp.) was used to perform statistical analysis. Normality and homogeneity of variance were assessed using the Shapiro-Wilk test and Levene's Test of Homogeneity, respectively. Assuming no, or only small, deviations in normality independent samples t-tests, which are shown to be robust to deviations from normality [29], were used to compare participant demographics and PTS between male and female participants. Multiple regression analysis was run to predict PTS from sex and 1) stature and 2) limb length. First, models were defined with sex and stature/limb length as independent variables. Then secondary models were defined where an interaction term for sex and stature/limb length was included. Reported p-values are adjusted using the Holm-Bonferroni method.

3. Results

The sex-specific mean, standard deviations (SD), and 95% confidence intervals (CI) of participant demographics are given in Table 1. The Shapiro-Wilk test of normality was significant for age and mass for female participants ($p = 0.032$ and $p = 0.008$, respectively) and PTS for male participants ($p = 0.019$). However, visual inspection of normal Q-Q plots suggested a normal distribution. Significant sex differences were observed for mass, stature, and average limb length, with female participants being 10 kg lighter, 0.11 m shorter, and having 0.06 m shorter limb lengths, on average, than male participants. No significant difference was found for age.

The sex-specific mean, standard deviations (SD), and 95% CI of PTS and Froude number are given in Table 2. The Shapiro-Wilk test of normality was significant for PTS for male participants ($p = 0.019$). After adjusting for multiple comparisons, no significant sex differences were found for either PTS. Although, it is also worth noting that two

Table 1
Participant demographics. Data are mean (SD).

	All participants (n = 37)	Female Participants (n = 19)	Male Participants (n = 18)	Sig. (2-tail)
Age [yrs.]	27 (6)	27 (6)	28 (7)	0.527
Mass [kg]	70.4 (12.4)	65.4 (13.8)	75.6 (8.1)	0.011[a]
Stature [m]	1.72 (0.08)	1.67 (0.07)	1.78 (0.04)	< 0.001[a]
Limb Length [m]	0.89 (0.05)	0.86 (0.05)	0.92 (0.03)	< 0.001[a]
Preferred Transition Speed [$m{\bullet}s^{-1}$]	1.9 (0.2)	1.8 (0.2)	1.9 (0.1)	0.026[a]

[a] indicates a significant difference after Holm-Bonferroni adjustment.

Table 2
Mulitple regression for preferred transition speed (PTS).

PTS	B	95% CI for B		sig.	R^2	ΔR^2
		LL	**UL**			
Model 1					0.241	0.194
Stature	0.89	0.05	1.74	0.039		
Sex	0.01	-0.12	0.15	0.837		
Model 2					0.471	0.420
Stature	1.70	0.85	2.55	≤ 0.001[a]		
Sex	5.05	2.25	7.86	0.001[a]		
Stature[a]Sex	-2.88	-4.49	-1.28	0.001[a]		
Model 3					0.252	0.205
Limb Length	1.24	0.12	2.36	0.030		
Sex	0.03	-0.08	0.15	0.558		
Model 4					0.293	0.224
Limb Length	3.46	-0.08	7.01	0.055		
Sex	1.74	-0.85	4.32	0.181		
Limb Length[a]Sex	-1.87	-4.70	0.97	0.189		

Note. Model= "Enter" method in SPSS. B is the unstandardized coefficient, CI is the confidence interval (LL=lower limit and UL=upper limit), R^2 is the coefficient of determination, and ΔR^2 is the adjusted R^2. Stature and limb length were measured in m, PTS was measured in m•s^{-1}.

[a] indicates significance after Holm-Bonferroni adjustment.

male participants (stature: (both) 1.77 m and limb length: 0.92 m and 0.90 m) did not transition by the final speed of 2.2 m•s^{-1}.

Visual inspection of partial regression plots and a plot of studentized residuals against the predicted values showed linearity and homoscedasticity. The Durbin-Watson statistic (2.490 for stature and 2.163 for limb length) indicated independence of residuals. Tolerance values were all greater than 0.1 indicating a lack of multicollinearity. There was no evidence of outliers (no studentized deleted residuals greater than ± 3 SD, leverage values greater than 0.22 for stature or 0.25 for limb length, or values for Cook's distance above 1). Visual inspection of the Normal P-P plot indicated normality.

The multiple regression model showed sex and stature explained 19% of the variance in PTS (Table 2- $F(2, 32)= 5.081$, $p \leq 0.012$, adj. $R^2 = 0.194$). After accounting for sex, a 10 cm increase in stature was associated with a 0.09 m·s^{-1} increase in PTS ($p \leq 0.039$). After accounting for stature, the model showed that PTS for male participants was 0.01 m·s^{-1} higher (on average) than for female participants ($p \leq 0.837$). However, when including the interaction between sex and stature the model explained 42% of the variance in PTS ($F(3, 31)= 9.194$, $p \leq 0.001$, adj. $R^2 = 0.420$). Furthermore, the interaction between sex and stature was significant ($p \leq 0.001$) and including it in the model showed that the slope of the relationship between stature and PTS differs by -2.884 between male and female participants (95% CI −4.49 −1.28).

The multiple regression model showed sex and limb length explained 21% of the variance in PTS (Table 2 - $F(2, 32)= 5.379$, $p \leq 0.010$, adj. $R^2 = 0.205$). After accounting for sex, a 10 cm increase in limb length was associated with a 0.12 m·s^{-1} increase in PTS ($p \leq 0.030$). After accounting for limb length, the model showed that PTS for male participants was 0.04 m·s^{-1} higher (on average) than for female participants ($p \leq 0.558$). However, when including the interaction between sex and limb length the model explained only 22% of the variance in PTS ($F(3, 31)= 4.278$, $p \leq 0.012$, adj. $R^2 = 0.224$). The interaction between sex and limb length was not significant ($B=-1.868$, $p \leq 0.1.89$, and 95% CI −4.70 0.97).

4. Discussion

This study aimed to determine the relationship between PTS and both stature and limb length and then examine the effect of sex on these relationships. The findings of this study partially support our hypothesis that there would be no sex differences in PTS and that both stature and limb length would have similar effects on PTS. However, our findings partially reject our hypothesis that sex would not affect these relationships.

Male participants had higher PTS than female participants, although non-significant after adjusting for multiple comparisons (Table 1). This finding is similar to published literature, which has consistently reported no significant sex differences in PTS [12,16,21]. PTS in this study (1.8 (0.2) m·s^{-1} and 1.9 (0.1) m·s^{-1} for female and male participants, respectively) are within the ranges reported in other studies (between 2.05 and 2.26 m•s^{-1} for male participants [12,16,20] and between 1.99 and 2.04 m•s^{-1} for female participants [12,16]). However, it is worth noting that the difference in PTS between male and female participants was significant at $p \leq 0.05$, before correcting for multiple comparisons, and just non-significant using the Holm-Bonferroni correction which suggests that the sample size may have been too small to detect a truly significant difference.

Multiple regression analysis showed that a model including sex, stature, and their interaction, accounted for 23% more of the variance in PTS than a model without the interaction term. Without the interaction, the model suggests that male participants have a PTS that is 0.01 m·s^{-1} higher, on average, than that for female participants of the same stature and that PTS would increase by 0.09 m·s^{-1} for each 10 cm increase in stature, regardless of sex. However, when including the interaction, between sex and stature, sex differences in the effect of stature on PTS become evident. The relationship between stature and PTS is 2.88 units more *negative* for male participants than that for female participants (Fig. 1). Essentially, for each 10 cm increase in stature PTS for female participants would increase by 0.17 m·s^{-1}, whereas PTS for male participants would *decrease* by 0.12 m·s^{-1}. This Simpson's paradox in the relationships between PTS and stature highlights the importance of investigating and interpreting sex differences in data. As seen in our results, by combining data from male and female participants there is a potential oversimplification of a more complex relationship and true sex-specific effects are obscured.

In contrast, the multiple regression analysis showed that a model including sex and limb length, and their interaction, only explained 2% more of the variance than a model without the interaction. This suggests that the interaction between sex and limb length does not significantly contribute to the explanatory power of the model. Using the model without the interaction term, female participants have, on average, a PTS that is 0.03 m·s^{-1} lower than that for male participants of the same stature and PTS increases by 0.12 m·s^{-1} for each 10 cm increase in stature, regardless of sex. Although looking at a plot of the data (Fig. 1), it appears that PTS should decrease as stature increases for male participants and increase as stature increases for female participants, similar, although weaker, to the relationships for stature. However, in this case, the confidence intervals do not rule out the possibility of the relationships between limb length and PTS being similar between male and female participants.

These findings contrast published literature. Both Hreljac [12] and Sentija, Rakovac and Babic [16] reported positive relationships between PTS and both stature and limb length for both male and female participants. They also reported stronger relationships for male participants compared with female participants [12,16]. However, somewhat similar to the findings of this study, Ranisavljev, Ilic, Soldatovic and Stefanovic [20] reported no clear correlation between PTS and stature ($r = 0.01$) and a negative correlation ($r = -0.31$) between PTS and limb length for male participants.

A broad range of correlation coefficients between PTS and stature have been reported for both male ($r = 0.01 – 0.50$) [12,16,20] and female ($r = 0.24 – 0.28$) [12,16] participants, as well as mixed cohorts ($r = 0.30 – 0.55$) [16,21]. There has also been a similarly broad range in correlation coefficients reported for PTS and limb length for both male participants ($r = -0.31$ to 0.49) [12,16,20] and female participants ($r = 0.20 – 0.35$) [12,16], as well as mixed cohorts ($r = 0.35 – 0.55$) [12,16,21]. Differences in correlation coefficients may be explained by the different treadmill protocols used, although Hreljac, Imamura,

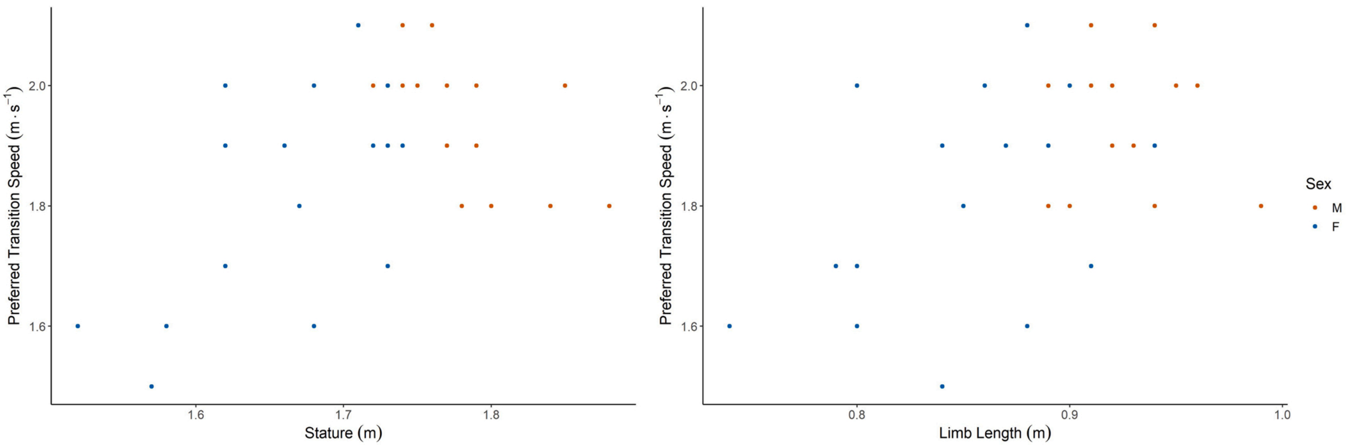

Fig. 1. Preferred transition speed against stature (left) and limb length (right) for male (M; orange circles) and female (F; blue circles) participants. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Escamilla and Edwards [13] found no difference in PTS from the constant acceleration protocol or the incremental protocol. Differences in populations investigated also may have contributed to differences in correlation coefficients. For example, differences in age, athleticism, and body morphology may also contribute to PTS, which aligns with the idea that the triggering mechanism for PTS is multifactorial [24,25].

As with any study, we must highlight some limitations. Firstly, there was a limited range in stature for male participants, 1.78 (0.04) m compared with 1.67 (0.07) m for female participants, which may have affected the correlations between PTS and both stature and limb length. However, Ranisavljev, Ilic, Soldatovic and Stefanovic [20], who included 59 male participants with a mean (SD) stature of 1.82 (0.06) m, found no relationship between PTS and stature ($r = 0.01$) and a moderate relationship between PTS and limb length (greater trochanter to floor; $r = -0.31$). Secondly, two participants in the current study did not transition by the final speed of 2.2 $m{\cdot}s^{-1}$. However, if these two male participants were given a hypothetical PTS of 2.3 $m{\bullet}s^{-1}$, 0.1 $m{\bullet}s^{-1}$ above the final speed used in this study, the overall findings do not change. The interaction between sex and stature was significant and the relationship between sex and stature was 3.04 units ($p \leq 0.002$) more *negative* for male participants than female participants. Including this interaction in the multiple regression model resulted in an 18% increase in the variance explained ($F(2, 34)= 5.792$, $p \leq 0.007$, adj. $R^2 = 0.210$) compared to the model without the interaction ($F(2, 34)= 8.556$, $p \leq 0.001$, adj. $R^2 = 0.386$). Similarly, for sex and limb length, the interaction between sex and limb length was non-significant ($p \leq 0.123$). These conflicting results, for stature and limb length, suggest the relationships between PTS and both stature and limb length are still not fully understood. This supposition is supported by Kung, Fink, Legg, Ali and Shultz [24] who argued that individual anthropometric characteristics do not trigger, but do influence, PTS. Therefore, it may be that within different populations (based on sex, age, athleticism, etc.) the importance of stature and limb length in influencing PTS varies. The triggering mechanism for PTS is likely multifactorial, including metabolic, cognitive, and biomechanical factors. Therefore, it is conceivable that aerobic and physiological capacities may influence the extent that stature and limb length influence PTS.

The findings of this study may have implications for the training and operational capability of individuals undertaking regimented activities. For example, military recruits who are required to complete timed field exercises or "keep together". This is also important given that the relationship between PTS and stature has been shown to vary between unloaded and loaded conditions [30] and thus some individuals may be required to run at speeds where others are comfortable walking, exposing them to higher external forces and potentially increased risks of injury.

5. Conclusion

This study found a significant interaction between sex and stature and its effect on PTS, with the relationship between stature and PTS in male participants being 2.88 units more *negative* than the relationship between stature and PTS in female participants. In contrast, there was no significant interaction between sex and limb length and its effect on PTS. These findings suggest that the influence of stature/limb length on transitions between walking and running gaits may differ between male and female participants. This highlights the importance of including both male and female participants in studies and the need to conduct sex-specific analysis of data.

Conflict of interest statement

There were no conflicts of interest for any authors.

Acknowledgements

This work was funded by the UK Ministry of Defence (Army).
Grant ID - ASC136.

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