Leg and lower limb dynamic joint stiffness during different walking speeds in healthy adults

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Abstract

Background: The differences and relationship between joint stiffness and leg stiffness can be used to characterize the lower limb behavior during different walking speeds.

Research question: This study aimed to investigate the differences in whole leg and lower limb joint stiffness at different walking speeds and the interactions between leg and lower limb joint stiffness.

Methods:

Twenty-seven healthy adults, seventeen males (age: 19.6±2.2 years, height: 176.0±6.0 cm, mass: 69.7±8.9 kg), and ten females (age: 19.1±1.9 years, height: 164.0±3.0 cm, mass: 59.6±3.8 kg), were recruited. Dynamic leg and joint stiffness were calculated during eccentric loading from data recorded using 3D infrared motion analysis and force plates at slow, normal, and fast walking speeds. Differences in dynamic stiffness, joint angles and moments were explored between the walking speeds using Repeated Measures ANOVA with Sidak post-hoc tests. Correlations between leg, joint stiffness, and walking speed were also explored.

Results:

The results indicated that the leg dynamic stiffness is decreased by walking speed, however, hip and ankle joint stiffness were increased ($p<0.001$) and knee stiffness was unaffected. Leg stiffness showed no correlation with hip, knee, or ankle stiffness. A positive significant correlation was seen between hip and ankle stiffness ($p<0.01$) and between knee and ankle stiffness ($p<0.001$), however, no correlation was seen between hip and knee stiffness.

Significance: These results suggest leg stiffness is not associated with lower limb joint stiffness during eccentric loading. This provides new information on the responses of ankle, knee and hip joint stiffness to walking speed.

Key words: Leg stiffness; Joint stiffness; Biomechanics; Walking speed.

1. Introduction

Many studies have reported stiffness of the lower limb during locomotion [1], which is often reported as leg stiffness or joint stiffness. Leg stiffness may be described as linear stiffness, the change of elastic deformation, or the change of force divided by the elongation [Leg stiffness=$\Delta F/\Delta x$]. Whereas joint stiffness may be defined as the change in moment divided by the change in angle [joint stiffness =$\Delta M/\Delta\theta$] [2], or defined as the ratio of maximal joint moment to maximum joint flexion angle [3-5]. Leg stiffness has been reported as the most suitable measure for evaluating the dynamic characteristics of the whole lower limb during walking or running [3, 6, 7]. However, joint stiffness has been linked to musculotendinous stiffness, which can be considered as passive or active [8]. Previous studies have defined passive stiffness as the characteristics of the joint structures without muscle activity [9-14], whereas dynamic stiffness, or quasi-stiffness, considers muscle activity interacting during inter-segmental displacements [15-20].

Several studies have investigated ankle joint stiffness during normal walking [2, 16, 17, 21-23], hip joint stiffness during normal walking [24], and leg stiffness during normal walking [3]. In addition, a few studies have investigated hip stiffness [25], knee stiffness [25, 26], ankle stiffness [25], and leg stiffness [27] during different walking speeds. Jin and Hahn [25] underlined the importance of investigating the relationship between joint stiffness and leg stiffness during different locomotion tasks and speeds. They indicated it may be beneficial to further investigate the relationship between joint stiffness and leg stiffness during different locomotion tasks and speeds. Furthermore, leg stiffness has been reported as a key parameter for understanding and describing human motion, and can be used to characterize the lower limb behavior during different walking speeds [28, 29].

The relationship between leg and joint stiffness is complex and has been shown to change according to walking and running speed, with some studies reporting an increase in leg stiffness [27, 30], whereas other studies indicate little difference when movements change from slow to moderate speeds [31-33], and Brughelli and Cronin [34] conversely reported that leg stiffness decreased at high velocity.

Brughelli and Cronin [34] and Kuitunen, Komi and Kyrolainen [35] indicated that knee joint stiffness plays a more important role in controlling leg stiffness than ankle joint stiffness. Kim and Park [27] reported the relationship between ankle and hip joint moments to be more sensitive with gait speed and indicated the importance of investigating the leg and lower limb joint stiffness at different walking speeds to quantify the contribution of the stiffness of each joint to leg stiffness. Therefore, our study investigated both leg and joint stiffness to increase our understanding of the role of joints stiffness in controlling overall leg stiffness during different walking speeds.

Thus, the purpose of the study was to determine the differences in leg stiffness and joint stiffness when walking at different speeds and to explore the relationships between leg stiffness and joint stiffness. We hypothesized that: (1) leg stiffness would alter during different walking speeds according to lower limb joints stiffness, (2) lower limb joints stiffness would increase when walking speeds increased.

2. Material and Methods

2.1. Subjects

Twenty-seven healthy adults, seventeen males (age: 19.6±2.2 years, height: 176.0±6.0 cm, mass: 69.7±8.9 kg), and ten females (age: 19.1±1.9 years, height: 164.0±3.0 cm, mass: 59.6±3.8 kg) volunteered to take part in the study. Subjects had no history of neural or musculoskeletal injuries of the lower limbs, and were free of pain and injury. All participants were informed of the experimental procedures and objectives and provided written informed consent to participate in this study, which was approved by the Ethical Committee for Human Research of the hosting institution.

2.2. Experiment Protocol

An 11 camera Qualisys motion analysis system (Qualisys AB, Gothenburg, Sweden) recorded three-dimensional kinematics at 200 Hz using a lower limb marker set consisting of 38 retro reflective markers placed on anatomical landmarks and rigid clusters. The markers were attached using double sided tape to; the anterior and posterior superior iliac spines, lateral and medial femoral epicondyles, lateral and medial prominence of the malleoli, posterior surface of the calcaneus, head of the 1st,

2^{nd} and 5^{th} metatarsal, greater trochanter, in addition clusters each with four markers were fixed to the thigh and shank using elastic bandages [36]. Participants were required to wear tight shorts in order to facilitate the marker placement and reduce motion artifacts. Four Bertec force platforms (Bertec Corporation, OH, USA), two 40x60 cm and two 60x90 cm, were used to record ground reaction force data at 1000 Hz, which was synchronized with the kinematic data using Qualisys Track Manager Software (Qualisys AB, Gothenburg, Sweden).

Participants were asked to walk at three different walking speeds; slow, normal, and fast. Before the commencement of data collection each participant was asked to perform a walk at their normal, most comfortable walking speed, and then instructed to practice walking at a slower speed between 80% and 85% of their normal speed, and then asked to increase their speed to between 115% and 120% of their normal walking speed. When the participants indicated they were confident in matching these speeds data collection commenced. Any slow or fast trials that were out of range of the target speed for each subject were ignored during data processing. Each participant performed walking trials along the length of a 12 m walkway, with at least three strides before and after reaching the force plates. Five successful trials at each speed were selected for analysis, and all variables were calculated and averaged across the 5 gait cycles for each speed for each subject.

2.3. Data Processing

Marker data were digitized using Qualisys Track Manager Software (Qualisys, Inc., Gothenburg, Sweden). Marker and force data were then exported to Visual3D for further analysis (C-Motion, Germantown, MD, USA).

2.4. Leg and Joint Stiffness

2.4.1. Leg Stiffness

The lower limb was modeled in accordance with previous work [37, 38]. Leg stiffness (k_{leg}) was calculated as the ratio of the peak vertical ground reaction force (vGRFpeak) to the change in vertical leg length (ΔL) during midstance, when the leg is at its maximal compression during stance phase, equation (1):

$$k_{leg} = \frac{vGRF_{peak}}{\Delta L} \qquad (1)$$

The maximum change in vertical leg length (ΔL) was calculated using the change in vertical leg length between initial contact and maximum displacement of the center of mass, and half of the sweep angle of the leg spring between these events, equations (2,3).

$$\Delta L = \Delta y + L_0(1 - \cos\theta) \qquad (2)$$

$$\theta = sin^{-1}(\frac{ut_c}{2L_0}) \qquad (3)$$

Where *vGRFpeak* = peak vertical force; *ΔL* = maximum change in vertical leg length; *Δy* = change in displacement of the center of mass; L_0 = leg length defined as the vertical distance from the ground to the greater trochanter during standing; *Θ* = half of the leg sweep angle arc by the leg spring between initial contact and maximum displacement of the center of mass; *u* = forward speed; t_c = the time of foot contact with the ground [38].

2.4.2. Joint Stiffness

Hip joint stiffness (K_{hip}), knee joint stiffness (K_{knee}), and ankle joint stiffness (K_{ankle}) were expressed by plotting the slope of the linear regression of sagittal plane values of flexion/extension moment versus flexion/extension angle over stance phase [22]. Joint stiffness was determined as the slope of the best fit line during single leg support between foot flat (FF) to heel lift (HL). Hip, knee, and ankle joint stiffness were quantified as previously described during the single leg support (Figure 1a, 1b, 1c), of the stance phase [7, 22, 39, 40]. Linear regression curves were fitted to the data by plotting joint angle against moment during single support phase for hip, knee, and ankle (Figure 1).

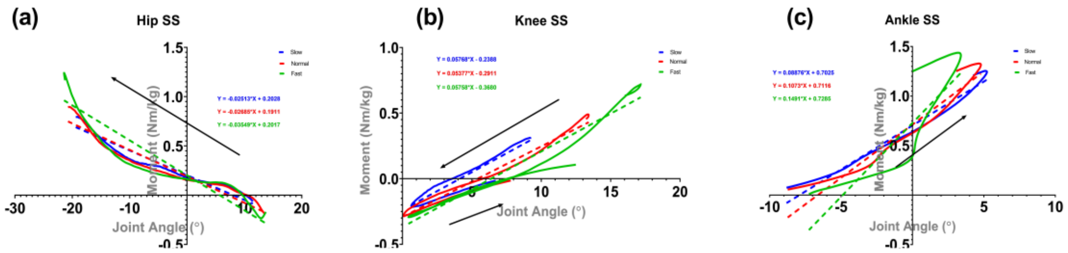

Figure 1. *Representative joint angle versus joint moment plot in the sagittal plane. The joint stiffness was calculated as the slope of the linear regression line from peak joint moment to peak joint angle or peak joint moment (whichever occurred first) during the single leg support phase (SS), (a) hip, (b) knee, and (c) ankle.*

Joint stiffness was calculated as the change in joint moment (ΔM) divided by the change in joint angle (ΔΘ) during stance phase, equation (4).

$$K_{joint} = \frac{\Delta M}{\Delta \theta} \quad (4)$$

where *ΔM* = change in joint moment; *ΔΘ*= change in joint angle [2, 7, 25].

2.5. Statistical analysis

The normality of the data were analyzed using Shapiro-Wilk tests and all data were found to be suitable for parametric analysis. Descriptive statistics were reported as means and standard deviations. Repeated Measures Analysis of Variance (ANOVA) with Sidak post hoc tests were used to compare the mean of each variable during stance phase for each subject between the three walking speeds. In addition, Pearson product-moment correlations were used to determine the relationship between walking speeds, leg stiffness, and joint stiffness. All statistical analysis were performed using IBM SPSS software Statistics v21.

3. Results

3.1. Walking Characteristics at Self-Selected Different Walking Speeds

Table 1 summarizes the comparison between the walking characteristics at the self-selected walking speeds; slow, normal, and fast. Means and standard deviations of speed, cycle time, stance time, step length, step time, stride length, swing time, and stride width are shown in table 1. Significant differences were found between speeds in all characteristics (*p<0.001*) with the exception of stride width (*p<0.680*) (Table 1).

Table 1. Walking Characteristics

Walking Characteristics	unit	Slow (n=27)		Normal (n=27)		Fast (n=27)		ANOVA P-Value
		Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	
Speed	m/s	0.939	0.059	1.120	0.084	1.412	0.102	<0.001
Cycle Time	s	1.269	0.072	1.105	0.067	0.925	0.058	<0.001
Stance Time	s	0.779	0.059	0.667	0.051	0.550	0.043	<0.001
Step Length	m	0.591	0.024	0.616	0.032	0.659	0.039	<0.001
Step Time	s	0.634	0.038	0.548	0.035	0.460	0.028	<0.001
Stride Length	m	1.184	0.039	1.234	0.052	1.310	0.061	<0.001
Swing Time	s	0.490	0.020	0.437	0.023	0.375	0.022	<0.001
Stride Width	m	0.127	0.023	0.132	0.023	0.126	0.029	=0.680

3.2. Leg stiffness and factors associated with leg stiffness at different walking speeds

The Repeated Measures ANOVA showed a significant main effect for speed for GRF, Θ, ΔL, and k_{leg} (*p<0.001*). Further post hoc tests showed significant increases between; slow and normal speed for GRF and Θ (*p<0.01*), ΔL (*p*<0.001), normal and fast for GRF and ΔL (*p<0.001*), and Θ (*p<0.01*), and between slow and fast for GRF, Θ and ΔL (*p<0.001*). Significant decreases were seen between; slow and normal speed for k_{leg} (*p<0.001*), and slow and fast (*p<0.05*), however no significant difference was seen between normal and fast walking for k_{leg}. In addition, a significant negative correlation was found between walking speed and k_{leg} (r=-0.262, *p<0.05*) (Figure 2).

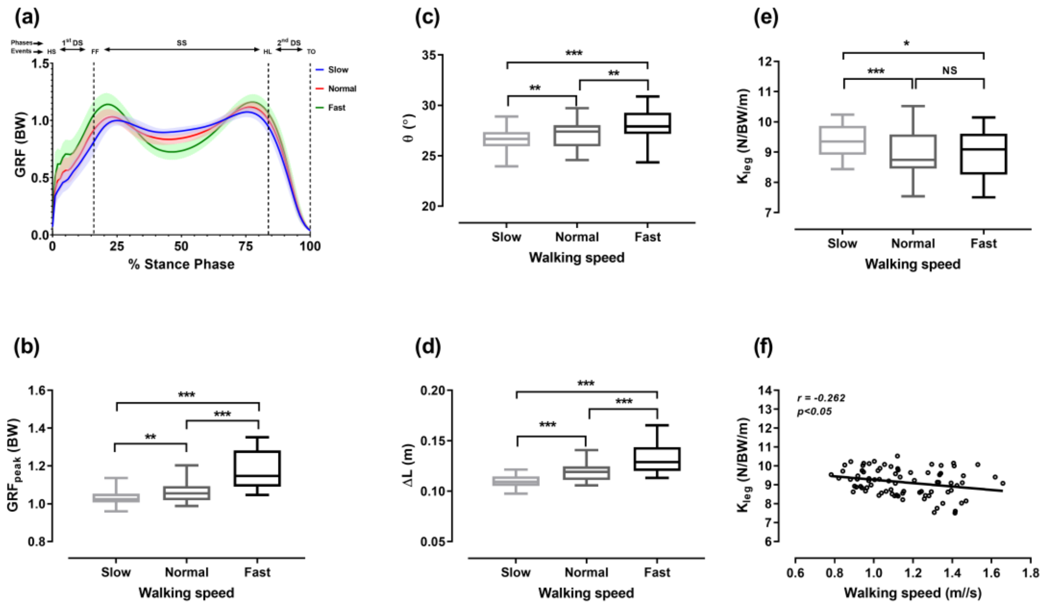

Figure 2. *Graphical representations of the ensemble means and standard deviation for GRF for each walking speed (a), box-and-whisker plots for the GRFpeak (b), leg sweep angle arc (c), vertical leg length during stance phase (d), leg stiffness Kleg (e), and correlation between walking speed and Kleg (f). Significant differences for the Post hoc tests between walking speeds (***) indicates a significance level of P<0.001 and (**) indicates a significance level of P<0.01.*

3.3. Joint stiffness and factors associated with joint stiffness at different walking speeds

3.3.1. Hip joint

The Repeated Measures ANOVA showed a significant main effect for speed for; hip joint angular displacement, change in hip moment and K_{hip} (*$p<0.001$*). Post hoc tests showed increases between; slow and normal, normal and fast, and slow and fast walking speeds for hip joint angular displacement, change in hip moment and K_{hip} (*$p<0.001$*). In addition, a significant positive correlation was found between walking speed and K_{hip} (r=0.665, *$p<0.001$*) (Figure 3).

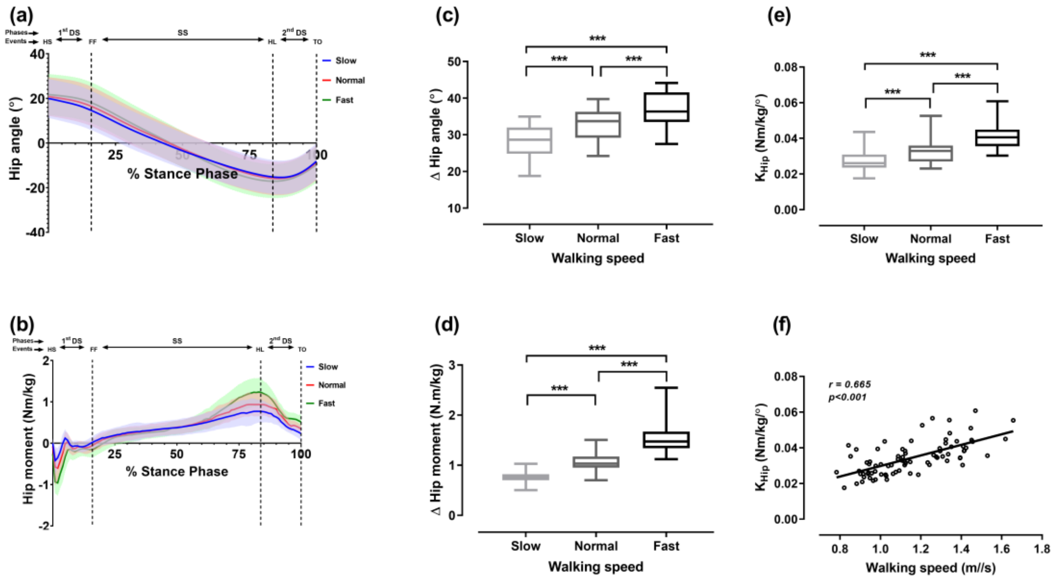

Figure 3. *Graphical representations of the ensemble means and standard deviation for hip angle (a) and hip moment (b). Box-and-whisker plots are presented for hip angle during stance phase (c) hip moment (d), hip joint stiffness (e), and the correlation between walking speed and Khip (f). Significant differences for the Post hoc tests between walking speeds (***) indicates a significance level of P<0.001.*

3.3.2. *Knee* joint

The Repeated Measures ANOVA showed a significant main effect for speed for; change in knee moment and knee angular displacement (*p<0.001*, *p<0.001*), respectively. Further post hoc tests showed increases between all speeds for change in knee moment and angle (*p<0.001*). However, no significant difference was seen for k_{knee} and no correlation was found between walking speed and K_{knee} (r=0.0276, *p=0.807*), (Figure 4).

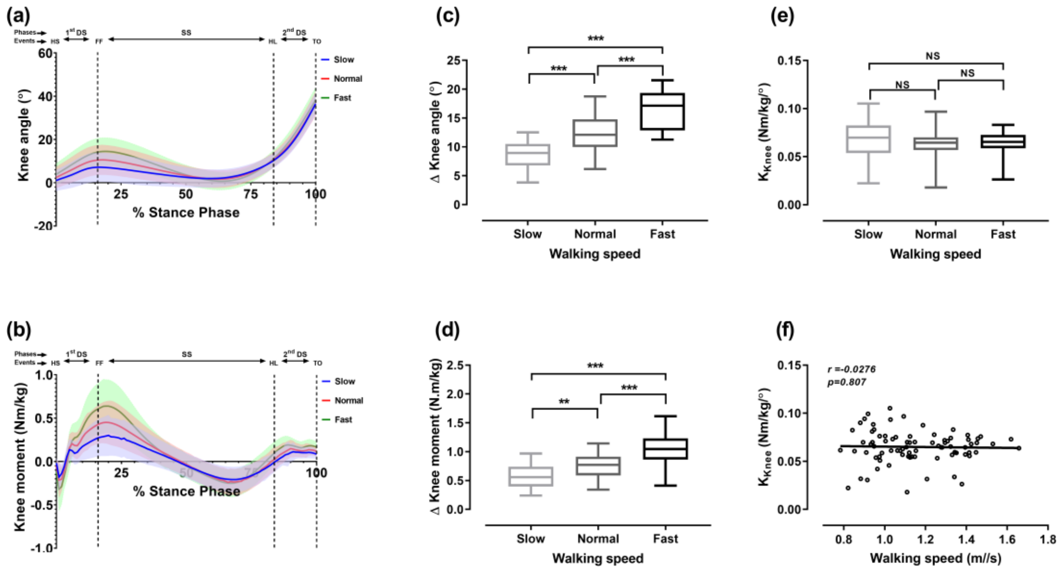

Figure 4. *Graphical representations of the ensemble means and standard deviation for knee angle (a) and knee moment (b). Box-and-whisker plots are presented for knee angle during stance phase (c) knee moment (d), and knee stiffness Kknee (e), correlation between walking speed and Kknee (f). Significant differences for the Post hoc tests between walking speeds (***) indicates a significance level of P<0.001 and (**) indicates a significance level of P<0.01.*

3.3.3. Ankle joint

The Repeated Measures ANOVA showed a significant main effect for speed for change in ankle moment, ankle angular displacement and K_{ankle} (*p<0.001*, *p<0.05*, *p<0.001*), respectively. Post hoc tests showed increases between slow and normal, normal and fast, and slow and fast walking speeds for change in ankle moment, between slow and normal, and normal and fast walking speeds for ankle angular displacement (*p<0.05*), and between slow and fast, and normal and fast walking speeds for k_{ankle} (*p<0.001*). However, no significant differences were seen between slow and fast, and slow and normal walking speeds for ankle angular displacement and $K_{ankle,}$ respectively. In addition, a significant positive correlation was found between walking speed and K_{ankle} (r=0.558, *p<0.001*) (Figure 5).

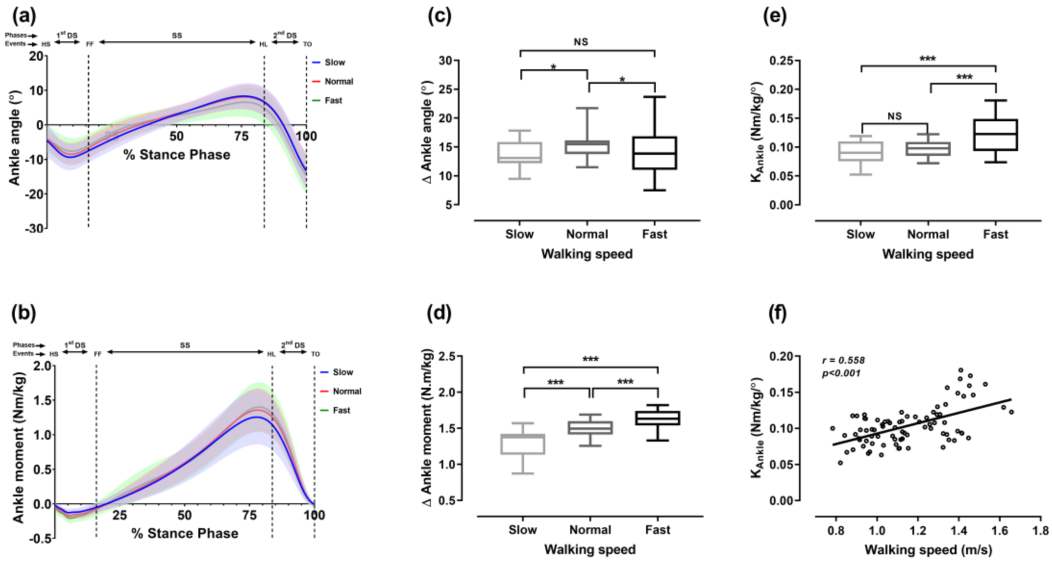

***Figure* 5.** *Graphical representations of the ensemble means and standard deviation for ankle angle (a) and ankle moment (b). Box-and-whisker plots are presented for ankle angle during stance phase (c) ankle moment (d), ankle stiffness Kankle (e), and correlation between walking speed and Kankle (f). Significant differences for the Post hoc tests between walking speeds (***) indicates a significance level of P<0.001, (**) indicates a significance level of P<0.01, and (*) indicates a significance level of P<0.05.*

3.4. Relationship between leg stiffness and joint stiffness

The correlations between leg stiffness and hip, knee, and ankle joint stiffness were investigated. A significant positive correlation was found between K_{hip} and K_{ankle} (*r=0.312; p<0.01*), and K_{knee} and K_{ankle} (*r=0.396; p<0.001*). However, no correlations were found between K_{hip} and K_{knee} (*r=0.139*; *p* =0.216), K_{leg} and K_{hip} (*r=0.175*; *p* =0.119), K_{leg} and K_{knee} (*r=0.049*; *p* =0.667), and K_{leg} and K_{ankle} (*r=0.208*; *p* =0.063).

4. Discussion

The purpose of the present study was to examine the differences in leg stiffness and joint stiffness during different walking speeds (slow, normal, and fast), and to investigate the relationship between walking speed and leg stiffness, walking speed and joint stiffness, and between leg and joint stiffness. Hip and ankle stiffness were quantified during single leg support of stance phase (Figure 1a, 1c) [22, 33, 34].

Knee joint stiffness has been previously described during the weight acceptance phase of gait, which was defined by shortly after initial contact (0–12% of the gait cycle) through the loading response phase of gait during which the impact of the ground reaction forces are absorbed [41, 42]. Nevertheless, we found a second knee joint stiffness slope fitted also during the single support phase (Figure 1b), Wang, Huang, Li, Hong, Lo and Lu [7] observed a high value of knee stiffness during mid-stance of healthy subjects (corresponding to the second rocker), and Frigo, Crenna and Jensen [43] indicated that the quasi-constant slope periods are detectable during single leg support during stance phase of gait. This current study provides important information and offers a greater understanding about the differences between leg stiffness, joint stiffness, and their relationship with walking speed. These findings show that there are significant differences between walking speeds for slow (0.94±0.06 m/s), normal (1.12±0.08 m/s), and fast (1.41±0.10 m/s) respectively (Table 1), which were in agreement with previous studies by Fox and Delp [44] who reported average walking speeds of 0.75 m/s for slow, 1.15 m/s for normal, and 1.56 m/s for fast, and 0.85 m/s for slow, 1.18 m/s for normal, and 1.43 m/s for fast reported by Khan, Khan and Usman [45]. However, this study also highlights the changes in components used to calculate leg stiffness with walking speed illustrating an increase in the peak GRF, Θ and ΔL among the different speeds [37, 38], with the increase in ΔL being proportionally greater than the increase in peak GRF between the walking speeds. With the percentage increase in ΔL between walking speeds, being 7.26% between slow and normal, 10.08% between normal and fast, and 16.62% between slow and fast. Whereas the associated percentage increases for peak GRF between walking speeds were, 2.59% between slow and normal speed, 9.86% between normal and fast, and 12.19% between slow and fast. This is in agreement with Brughelli and Cronin [34] who indicated that the increase in the slope of the GRF and ΔL curve indicates an increase in stiffness, so the leg stiffness from the current study was decreased due to the increase in ΔL being greater than that of the GRF. This resulted in a significant decrease in leg stiffness with an increase in walking speed between slow and normal ($p<0.001$), slow and fast ($p<0.05$), and no difference between normal and fast walking speed, which was supported by a negative correlation between leg stiffness and walking speed.

The hip and ankle joint stiffness showed a positive significant increase with walking speed, with the hip stiffness showing significant differences between all three speeds, and an associated high positive correlation with speed. Similarly, the ankle stiffness showed differences between slow and fast and between normal and fast speeds with a significant positive correlation with speed. An unexpected result in the current study was seen for knee stiffness, which indicated no differences between all speeds with no correlation with speed. This result may be due to a low dynamic moment with respect to the knee angular displacement during the selected phase (SS). The nature of this relationship is associated with a smaller knee angular displacement and greater knee extensor moment producing a greater walking knee stiffness [26, 42], this interpretation is in agreement with Shamaei, Sawicki and Dollar [46] who found that the knee stiffness increased during knee flexion phase, but then decreased during knee extension in the weight acceptance phase.

The findings from the hip stiffness are in agreement with previous studies [43, 47], and depend on the relationship between hip moment versus the hip angle during walking. The significant positive correlation for ankle stiffness was in agreement with previously reported findings [25], in addition the difference in response to the hip and knee stiffness appears to not be associated with a greater stiffness adaptability which is also in agreement with previous studies [43, 48]. The differences in decrease leg stiffness between walking speeds with the increase in hip and ankle stiffness, indicates a coordination of the lower limb joint stiffness to provide changes in control during walking at different speeds [49]. To the authors' knowledge this is the first study that examined the leg and lower limb joints stiffness concurrently, as well as the exploration of the relationships between the components of the calculations of stiffness with respect to walking speed [25]. However, the question remains whether this difference in response is associated with passive versus active joint stiffness and its association with motor control. Therefore, future work should further examine the relationship between joint and leg stiffness, and muscle activity to explore this phenomenon in terms of passive versus active joint stiffness.

5. Conclusion

Leg stiffness is decreased by walking speed, however hip and ankle joint stiffness were increased. Leg stiffness showed no relationship with hip, knee, and ankle stiffness. However, positive relationships were seen between hip and ankle stiffness and between knee and ankle stiffness, indicating that the knee may be acting independently to modify leg stiffness. These findings help highlight differences in response in lower limb stiffness and lower limb joint and suggest that leg stiffness is not associated with lower limb joint stiffness during eccentric loading. This provides new information on the responses of ankle, knee and hip joint stiffness to walking speed.

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