1 Individual Muscle Contributions to Tibiofemoral Compressive Articular Loading
2 during Walking, Running and Sidestepping

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Abstract:

The tibiofemoral joint (TFJ) experiences large compressive articular contact loads during activities of daily living, caused by inertial, ligamentous, capsular, and most significantly musculotendon loads. Comparisons of relative contributions of individual muscles to TFJ contact loading between walking and sporting movements have not been previously examined. The purpose of this study was to determine relative contributions of individual lower-limb muscles to compressive articular loading of the medial and lateral TFJ during walking, running, and sidestepping. The medial and lateral compartments of the TFJ were loaded by a combination of medial and lateral muscles. During all gait tasks, the primary muscles loading the medial and lateral TFJ were the vastus medialis (VM) and vastus lateralis (VL) respectively during weight acceptance, while typically the medial gastrocnemii (MG) and lateral gastrocnemii (LG) dominated medial and lateral TFJ loading respectively during mid-stance and push-off. Generally, the contribution of the quadriceps muscles were higher in running compared to walking, whereas gastrocnemii contributions were higher in walking compared to running. When comparing running and sidestepping, contributions to medial TFJ contact loading were generally higher during sidestepping while contributions to lateral TFJ contact loading were generally lower. These results suggests that after orthopaedic procedures, the VM, VL, MG and LG should be of particular rehabilitation focus to restore TFJ stability during dynamic gait tasks.

1 Introduction

2 During walking, muscles stabilize the knee, i.e. prevent lateral tibiofemoral joint (TFJ)
3 compartment unloading (condylar lift-off) (Lloyd and Buchanan, 2001; Schipplein and
4 Andriacchi, 1991; Shelburne et al., 2006; Winby et al., 2009). However, this TFJ stabilization
5 increases compressive contact loading applied to both the medial and lateral TFJ articular
6 surfaces (Brandon et al., 2014; Sasaki, 2010; Schipplein and Andriacchi, 1991), suggesting a
7 trade-off between joint stability and joint contact loading (JCL). However, the dual roles of
8 muscle in TFJ stabilization and JCL likely change between gait tasks, due to task-specific
9 kinematics (Schwartz et al., 2008), external loads (Besier et al., 2001; Schwartz et al., 2008),
10 coordination of positive joint work (Novacheck, 1995), and muscle activation patterns
11 (Besier et al., 2003).

12 The majority of studies examining muscular loading of the TFJ considered only a single
13 mode of gait, e.g., walking (Sasaki, 2010; Shelburne et al., 2006; Sritharan et al., 2012;
14 Winby et al., 2009), running (Pandy and Andriacchi, 2010; Sasaki, 2010), or drop-landing
15 (Tsai et al., 2012). Only a single study (Saxby et al., 2016) examined muscular loading to,
16 and stabilization of, the TFJ between different gait tasks, i.e., walking, running and
17 sidestepping. Collectively, previous studies suggest muscle contributions to TFJ contact
18 loading and stabilization are task- and muscle-specific, but this remains to be conclusively
19 demonstrated. Elucidating the roles of specific muscles in TFJ contact loading and
20 stabilization may be of particular relevance to those undergoing rehabilitation following
21 orthopaedic procedures. Indeed, this knowledge might inform rehabilitation programs to
22 target muscles important to stabilization in vulnerable populations, e.g., patients with anterior
23 cruciate ligament (ACL) reconstruction who are at risk of re-rupture (Ahn et al., 2007) and
24 knee instability (Daniel et al., 1994). Furthermore, and as highlighted in a recent review

(Trinler et al., 2018), there is a scarcity of literature data that details the contribution of muscle forces to JCL across a range of tasks, a gap that needs to be addressed.

Sidestepping (i.e. side-step cutting) is a common sporting manoeuvre that is associated with ACL rupture (Cochrane et al., 2007). To date, studies of sidestepping have examined net muscle contributions to JCL (Saxby et al., 2016) or effects of muscle fatigue on ACL strain (Weinhandl et al., 2013, 2014), leaving the roles of individual muscles to TFJ contact loading and stabilization unexplored. Moreover, the majority of studies examining TFJ contact loading used optimization-based methods to predict muscle activations (Pandy and Andriacchi, 2010; Sasaki, 2010; Shelburne et al., 2006; Sritharan et al., 2012), which operate by enforcing *a priori* mathematical criteria when solving the general distribution problem (Crowninshield, 1981) of muscular load sharing about joints. Critically, optimization-based methods predict lateral compartment unloading (Kim et al., 2009; Lin et al., 2010) during walking, contrary to direct measurement from instrumented implants (Fregly et al., 2012; Fregly et al., 2009). Optimization-based muscle activation predictions are also dependent on the degrees of freedom (DOF) present in the joint model (Jinha et al., 2006), and fail to predict many features of experimentally-observed muscle coordination, e.g., load sharing (Binding et al., 2000), antagonistic activation (Herzog and Binding, 1992), and co-contraction (Herzog and Binding, 1993). As sidestepping and straight-line running elicit high-levels of knee muscle co-contraction (Besier et al., 2003), optimization-based methods may not be well-suited to modelling muscle stabilization of the TFJ in these types of gait tasks. A few studies (Buchanan et al., 2004; Saxby et al., 2016; Tsai et al., 2012; Winby et al., 2009) have used electromyography- (EMG) driven approaches, which incorporate experimentally acquired subject- and task-specific muscle excitations, to investigate TFJ contact loading and muscle stabilization.

Subsequently, using an EMG-driven modelling approach, the primary aim of this study was to examine how knee-spanning muscles load, and subsequently stabilize, medial and lateral TFJ compartments during walking, running, and sidestepping. The secondary aim was to assess whether muscle contributions to TFJ contact loading/stabilization change between gait tasks and across stance phases. Our first hypothesis (H_1) was that during walking vastus medialis (VM) and medial gastrocnemii (MG) would dominate medial TFJ contact loading, and lateral TFJ would be loaded primarily by vastus lateralis (VL) and lateral gastrocnemii (LG). Further, based on changes in joint function across gait tasks, i.e. hip versus ankle power generation strategies (Novacheck, 1995), it was hypothesized (H_2) that the MG and LG would make larger contributions to TFJ contact loading during walking compared to running, while the rectus femoris (RF), vastus intermedius (VI), VM, VL, semimembranosus (SM), semitendinosus (ST), biceps femoris long head (BFLH), and biceps femoris short head (BFSH) muscles would make larger contributions during running compared to walking. Our third hypothesis (H_3) was that during running and sidestepping, medial TFJ loading would be dominated by VM, SM, and ST, while the VL, BFLH, and BFSH would dominate lateral TFJ contact loading. Finally, due to the greater requirement for medial TFJ stabilization in sidestepping compared to running, it was hypothesised (H_4) that medial muscle contributions to medial TFJ loading would be larger in sidestepping.

Methods

For detailed descriptions of data collection and TFJ contact load estimations, refer to our previously published study (Saxby et al., 2016). Briefly, motion analysis data were collected at Griffith University's School of Allied Health Sciences (AHS) and University of Melbourne's Centre for Health, Exercise and Sports Medicine (CHESM). Human research ethics approval was provided from each University (AHS: PES/36/10/HREC, CHESM: 0932864.3). Fifty-five individuals (22 female) participated with mean $\pm$ standard deviation

for age, height, and mass of 27.3 ± 5.4 years, 1.75 ± 0.11 m, and 69.8 ± 14.0 kg, respectively. During motion analysis, participants wore a full-body retro-reflective marker set and bipolar surface electrodes placed over 8 major knee muscles: the RF, VM, VL, MG, LG, medial hamstrings, lateral hamstrings, and tensor fascia latae (TFL). Participants completed four repetitions of each gait task: walking at a self-selected speed, running at $4\text{--}5 \text{ m}\cdot\text{s}^{-1}$, and 45° sidestepping at a maximal self-selected speed.

We used a modified OpenSim Gait2392 model, with the addition of upper-limbs. Overall, the model contained 25 bodies, interconnected by 24 joints, with 54 DOF and actuated by 68 muscles. In this a two point TFJ contact model (Schipplein and Andriacchi, 1991; Winby et al., 2009) was implemented as a four body model as per Saxby et al. (2016), which had three rotational DOF: flexion/extension, adduction/abduction, and tibial internal/external rotation. Anterior/posterior and superior/inferior tibial translations were prescribed as functions of knee flexion (Yamaguchi and Zajac, 1989). Generalized coordinates for all DOF were solved with marker trajectories from motion capture using the Inverse Kinematics tool in OpenSim (Delp et al., 2007). To prevent non-physiological TFJ motion, the abduction/adduction and internal/external rotations were constrained within $+5/-5$ and to $+15/-5$ degrees, respectively, based on measurements from cadavers (Kanamori et al., 2002) and *in vivo* study using intra-cortical bone pins (Benoit et al., 2006).

Using the OpenSim model, Calibrated EMG Informed Neuromusculoskeletal (CEINMS) toolbox (Pizzolato et al., 2015) was employed to estimate muscle and TFJ contact forces. In this, the EMGs were used to map the activation of 11 musculotendon actuators (MTUAs) using previously described methods (Sartori et al., 2012), which assumes MTUAs sharing a common nerve exhibit identical activation patterns. The 11 MTUAs were: RF, VM, VL, VI, BFLH, BFSH, SM, ST, MG, LG, and TFL. CEINMS was used to first calibrate MTUA parameters using a three trials, one from each gait task, and then run in execution mode to

estimate MTUA forces and muscle generated joint moments for the remaining trials (Pizzolato et al., 2015; Sartori et al., 2012; Saxby et al., 2016). MTUA forces from CEINMS and moment arms from OpenSim were used to calculate MTUA moments relative to both the medial and lateral TFJ contact points, using the method presented in Winby et al. (2009) (see Equation 1). This model uses regression equations based on femoral width to define the position of medial and lateral TFJ contact points, and assumes the moments about one contact point were balanced by a combination of muscle and contact moments (due to joint reaction forces) about the opposite contact point. This model relies on three assumptions, firstly that only forces with a component which acts parallel to the long axis of the tibia or generate an abduction/adduction moment contribute to TFJ contact loading. Secondly that these forces act through the two contact points (one medial and one lateral). Finally, ligaments do not contribute to the loading of the articular surfaces.

$$\begin{aligned} \mathbf{M}_i^{MC} &= F_i^M \times r_i^{MC} \\ \mathbf{M}_i^{LC} &= F_i^M \times r_i^{LC} \\ \mathbf{M}_i^{cont(MC)} &= \frac{M_i^{LC}}{M_{muscle}^{LC} + M_{external}^{LC}} \\ \mathbf{M}_i^{cont(LC)} &= \frac{M_i^{MC}}{M_{muscle}^{MC} + M_{external}^{MC}} \end{aligned}$$

Equation 1

Where M_i^{MC} and M_i^{LC} are i^{th} muscle moments, r_i^{MC} and r_i^{LC} are i^{th} muscle moment arms and $M_i^{cont(MC)}$ and $M_i^{cont(LC)}$ are i^{th} muscle's contribution to loading relative to the medial and lateral TFJ compartment respectively. M_{muscle}^{MC} and M_{muscle}^{LC} are muscle moments summed about the medial and lateral TFJ contact points, and $M_{external}^{MC}$ and $M_{external}^{LC}$ are external frontal plane moments summed about the medial and lateral TJF contact points, and F_i^M is i^{th} muscle's force. The individual relative muscle contributions ($M_i^{cont(LC/MC)}$) to each

compartments loading were expressed as a percentage of the summed muscle and external moments ($M_{muscle}^{MC/LC} + M_{external}^{MC/LC}$).

Stance was divided into three phases based on knee flexion/extension kinematics: weight acceptance (WA), mid-stance (MID), and push-off (PO) (see Figure 1). A 10 N threshold was used to define the beginning and end-of stance. WA phase was between initial foot contact and the first trough in knee flexion/extension. MID phase began directly after WA for all gait tasks, while end-of-MID was defined as first peak in knee flexion/extension angle during walking (see Figure 1A), and the point-of-inflection of the knee flexion/extension angle in running and sidestepping (see Figure 1B and C respectively). Finally, the PO phase was from end-of-MID to toe-off.

Multifactor repeated measures ANOVAs were used to determine main effects of, and interaction between, gait task, stance phase, TFJ compartment, and individual muscle. When significant main and interaction effects were found, Bonferroni *post-hoc* tests were performed to determine specific muscle differences. Statistical significance was set at $p < 0.05$, with all analyses performed in SPSS v22 (IBM, Armonk, NY). Relative contributions of individual muscles to TFJ contact loading were compared within stance phases and within gait tasks to determine dominant contributors to TFJ contact loading. Muscle contributions were compared between gait tasks and within stance phases to determine task differences.

Results

The average gait speed for all participants was $1.44 \pm 0.22 \text{ m.s}^{-1}$, $4.38 \pm 0.42 \text{ m.s}^{-1}$, and $3.58 \pm 0.5 \text{ m.s}^{-1}$ during walking, running, and sidestepping, respectively. Generally, during WA, medial and lateral compartment contact loading was dominated by VM and VL respectively, while during MID and PO medial compartment contact loading was dominated by MG for all gait tasks (Figures 2, 3, and 4: Table 1).

Percentage contributions to TFJ contact loading changed between walking and running, and between running and sidestepping (Figures 5 and 6: Table 2). During WA, percentage muscle contributions were generally higher in walking compared to running, with the exception of RF, VI, and VL. During MID and PO, percentage muscle contributions were typically higher during running, with the exception of MG and LG. When comparing running and sidestepping, percentage muscle contributions to medial compartment loading were typically larger in sidestepping, whereas percentage muscle contributions to lateral compartment loading were typically higher in running.

Discussion

This was the first study to examine relative contributions of individual muscles to medial and lateral TFJ contact loading during walking, running and sidestepping. Our hypotheses were largely confirmed, as contributions of individual muscles to TFJ contact loading changed across stance phases (H_1 and H_3) and between gait tasks (H_2 and H_4). Future investigations may use this information to inform rehabilitation or conditioning programs for individuals based on the muscular stabilization requirements of commonly performed tasks.

Walking results partially confirmed H_1 and were consistent with previous literature (Shelburne et al., 2006; Sritharan et al., 2012; Winby et al., 2009). During walking MG and LG were found to dominate medial and lateral TFJ contact loading respectively, during MID and PO. Also consistent with the literature, vastii (VM and VL) and hamstring (SM and BFLH) muscles dominated medial and lateral TFJ contact loading during WA. Contrary to Winby et al. (2009), who estimated ~25% of lateral TFJ contact loading in walking were due to TFL, we only found a low ~7% contribution (Figure 2). This may be due, in part, to different modelling techniques. Winby et al. (2009) combined two different software (i.e., BodyBuilder and SIMM) and a direct kinematics approach, with unconstrained motion estimation. We used one software for all modelling (i.e., OpenSim) and an inverse kinematics

approach, which constrained TFJ kinematics to prevent non-physiologic motions, such as distraction and interpenetration. Traditional motion capture (i.e., based on skin-surface mounted markers) combined with direct kinematics calculations result in inaccurate measures of non-sagittal knee rotations (Benoit et al., 2006) due to soft tissue artefact (Stagni et al., 2005). This may have resulted in larger knee adduction angles and moments in Winby et al. (2009). Moreover, the TFJ contact model used in both studies is sensitive to the magnitude of the external frontal plane moment. Increased external knee adduction moments need to be supported by increased lateral muscle moments, of which the TFL is a member. Finally, Winby et al. (2009) used a single DOF calibration whereas this research used a multi DOF calibration, which has previously been shown to result in different MTUA force estimations, particularly two-joint muscles, i.e. RF, hamstrings and gastrocnemii (Sartori et al., 2012).

Previous studies of running investigated net muscle (Saxby et al., 2016) or grouped muscle (Sasaki, 2010) contributions to JCL, or contributions to body acceleration (Hamner and Delp, 2013; Hamner et al., 2010). A conclusion common to these studies was that the quadriceps are dominant during early stance, while hamstrings and gastrocnemii are dominant during mid-to-late stance. Partially confirming H₃, our results are consistent with these prior reports, indicating VM and VL are dominant contributors to medial and lateral TFJ contact loading during WA, respectively. Similarly, MG dominates contribution to medial TFJ contact loading during MID and PO. Contrary to prior reports, during MID, the VL, and BFLH dominate contribution to lateral TFJ contact loading with no significant main effect of muscle during PO. The results for running show a striking resemblance to walking, with selected quadriceps muscles dominant during WA and the gastrocnemii muscles dominate during MID and PO. This is unsurprising due to straight line nature of both tasks; however, these conclusions cannot be readily extended to non-straight line tasks such as sidestepping.

Previously only three studies (Saxby et al., 2016; Weinhandl et al., 2013, 2014) have considered muscular contributions during sidestepping. Weinhandl et al. (2013) and Weinhandl et al. (2014), when examining the muscular support of the ACL, speculated that the vastii act together to increase TFJ compression during sidestepping, which was confirmed by Saxby et al. (2016). Now for the first time we have shown that during WA medial and lateral TFJ contact loading was dominated by VM and VL, respectively, partially confirming H₃. Additionally, MG dominated contribution to medial TFJ contact loading during MID and PO, but no difference was shown with respect to lateral TFJ compartment. In addition to contributing to loading, these muscles are also responsible for providing stabilization of the TFJ. This suggests these muscles (VM, VL and MG) should be strengthened to provide stability during sidestepping to potentially reduce the risk of ACL rupture. These results may seem intuitive as muscles with largest abduction/adduction moment arms, and which provide substantial body propulsion (Novacheck, 1998), contribute most to TFJ contact loading. Although interestingly, almost the same muscles are dominant for all three gait tasks, despite differences in kinematics (Novacheck, 1998) , kinetics (Novacheck, 1998) , and TFJ contact loads (Saxby et al., 2016). Regardless of the task, VM, VL, MG, and LG provide the majority of muscle stabilization of the TFJ. Therefore, strengthening and coordinating VM, VL, MG, and LG to ensure adequate TFJ stability should be a priority following TFJ orthopaedic procedures, although stability may come at the expense of increased TFJ contact loading, which has previously been linked to an increased risk of osteoarthritis development (Andriacchi et al., 2009).

We found a number of changes in muscle contributions to TFJ contact loading between walking and running due to task-specific kinematics and kinetics (see Table 2). Hip joint positive powers increase and ankle joint positive powers decrease during running compared to walking (Novacheck, 1995). This was reflected in our results where MG and LG

contributions to medial and lateral TFJ contact loading were higher in walking compared to running during MID and PO thereby confirming H₂. Further confirming H₂, the VI, VM, VL, SM, ST, BFLH, and BFSH contributions to medial and lateral TFJ contact loading were higher in running compared to walking during MID and PO. Additionally, increased contributions from VL, BFLH, and BFSH from walking to running reflect a more laterally directed muscle activation strategy to counteract the larger knee adduction moment present during running (Schwartz et al., 2008). Interestingly, during WA, the SM, ST, and BFLH contributions to medial and lateral TFJ contact loading were higher in walking compared to running, but the same muscles' contributions during PO were higher during running compared to walking. This higher contribution during WA in walking may be caused by active hamstring-driven hip extension, which, during running, may occur more passively as it is assisted by higher amounts of limb momenta. We observed an increase in TFL relative contribution to TFJ contact loading during walking compared to running, perhaps due to changes in the muscle's adduction moment arm, which decreases as knee flexion increases (Lloyd and Buchanan, 2001), and since larger knee flexion occurs during running compared to walking (Schwartz et al., 2008). These results again highlight the importance of VM and VL in stabilizing the medial and lateral TFJ compartments, especially when performing vigorous movements such as running.

A number of differences were also apparent comparing relative muscle contributions during running and sidestepping. H₄ was partially confirmed with higher contributions by medial muscles although differences were also shown in lateral muscles. A clear, counter intuitive pattern was seen across all stance phases. Various muscles, irrespective of if they were medial (VM, SM, MG), lateral (VL, LG) or neither (RF, VI) based on their moment arms, increased their contributions to medial TFJ contact loading and decreased their lateral TFJ contact loading contributions in sidestepping compared to running (see Table 2). These

changes are likely driven by differences in knee adduction/abduction moment between tasks; the TFJ experiences a predominantly external knee abduction moment in sidestepping, unlike running where an external knee adduction moment is present. An abduction moment, if unsupported, tends to compress the lateral and unload the medial compartment (Besier et al., 2003). Therefore, during running, muscle action is required to stabilize the lateral TFJ compartment, while muscle stabilization of the medial TFJ is required during sidestepping. These results emphasise the importance of VM, VL, MG, and LG to the stabilization of the TFJ, and highlights the importance of recruitment of RF, VI, VM, VL, SM, MG and LG during vigorous sporting manoeuvres such as sidestepping. This has particular relevance to those undergoing ACL reconstruction, where substantial muscle volume losses have been reported for the ST, Gracilis, and VM muscles (Konrath et al., 2016). These muscles provide critical TFJ stabilization during sidestepping. Given the high risk of ACL re-rupture (Ahn et al., 2007) and the association between ACL rupture and sidestepping (Cochrane et al., 2007), if these muscles are weak and/or not-recruited this would increase re-rupture risk.

There are a number of limitations to this study. First, the anatomic model was personalized to each participant through linear scaling and muscle parameter optimization, but was not truly subject-specific. Musculoskeletal geometry influences modelled external joint and internal muscle moments, and hence both absolute and relative contributions to TFJ contact loading. Additionally, the position of the medial and lateral TFJ contact points have previously been shown to affect TFJ contact load estimates (Gerus et al., 2013; Lerner et al., 2015), although we did scale the generic contact point positions based on the individual knee widths using a linear model built from imaging data (Saxby et al., 2016; Winby et al., 2009). Second, the CEINMS model MTU parameters governing muscle force predictions, and subsequent TFJ contact load estimates, were taken from literature and calibrated within physiological bounds. Nonetheless, calibration is a functional procedure to ensure a very good fit between model

and inverse dynamics joint moment calculations, and may not necessarily result in accurate subject-specific MTU parameters. This may result in muscle forces which equilibrate the system; but are inaccurate. However, the multi-DOF model used in this study has been shown to produce calibrations that generate physiological plausible MTU parameters and forces estimates (Sartori et al., 2012). Furthermore, the CEINMS model TFJ joint contact load estimations have been verified using instrumented prosthetic data during walking (Gerus et al., 2013; Saxby et al., 2016), although it has not been verified for running and sidestepping. This is understandable, as implant patients are discouraged from performing such vigorous tasks due to risks to the implant. However model predictions have been consistent with previous literature (Fregly et al., 2012; Fregly et al., 2009), where comparisons were possible, we have shown accurate predictions of joint moments (Lloyd and Besier, 2003) and TFJ contact loads (Gerus et al., 2013; Serrancoli et al., 2016; Walter et al., 2014; Wu et al., 2016). Finally, the assumptions of the TFJ contact model potentially effect the estimated joint contact loads and subsequently estimations of muscle contributions to TFJ stabilization. Specifically, neglecting the contributions of ligaments to TFJ stabilization may have increased the magnitude of muscle stabilization. While this limitation is acknowledged, previous studies have shown that the contribution of muscles are much greater than ligaments during stance (Shelburne et al., 2006) nonetheless the reported magnitudes may have been overestimated.

Our results indicate the magnitude of muscle relative contributions to medial and lateral TFJ contact loading are task-specific, although dominant muscles show similarities. Typically the VM and VL muscles dominant medial and lateral TFJ contact loading respectively during WA. Additionally, during MID and PO, the MG and LG were dominant to medial and lateral TFJ contact loading respectively. When comparing walking and running, RF, VM, VL and VI contributions to TFJ contact loading were typically higher during running while MG and

LG contributions were higher in walking. When comparing running and sidestepping, selected muscle contributions to medial TFJ contact loading were higher in sidestepping while selected muscle contributions to lateral TFJ contact loading were higher in running. This information may enable targeting of specific muscles to support the TFJ in vulnerable populations, such as those following orthopaedic interventions. Particular focus should be placed on recruiting VM, VL, MG, and LG for gait tasks such as waking and straight line running. While additional focus should be placed on the medial musculature, VM, SM, ST, and MG, during high-risk manoeuvres such as sidestepping.

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Conflict of interest statement

All authors' state there are no conflicts of interest with regarding to any of the presented work.

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Figure 1. Tibiofemoral flexion/extension throughout the stance phase of walking (A), running (B), and sidestepping (C) indicating the definition of weight acceptance (WA), mid-stance (MID) and push off (PO) phases of stance.

Figure 2. Individual (average $\pm$ standard error) muscle contributions to medial and lateral TFJ loading during walking gait. Muscles are grouped according to their ability to produce an abduction or adduction moment relative to the TFJ centre.

Figure 3. Individual (average $\pm$ standard error) muscle contributions to medial and lateral TFJ loading during running gait. Muscles are grouped according to their ability to produce an abduction or adduction moment relative to the TFJ centre.

Figure 4. Individual (average $\pm$ standard error) muscle contributions to medial and lateral TFJ loading during sidestepping gait. Muscles are grouped according to their ability to produce an abduction or adduction moment relative to the TFJ centre.

Figure 5. Average ($\pm$ standard error) individual muscle relative contributions to medial TFJ loading during the WA, MID, and PO stance phases of walking, running, and sidestepping.

Figure 6. Average ($\pm$ standard error) individual muscle relative contributions to lateral TFJ loading during the WA, MID, and PO stance phases of walking, running, and sidestepping

Figure 1

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Table 1

Table 1. Dominant muscle(s) contributors to and average ($\pm$ standard error) magnitudes of medial and lateral TFJ contact loading during walking, running, and sidestepping for each phases of stance. Where NS = No significant main effect or interaction.

	Weight acceptance		Mid-stance		Push-off	
	Medial	Lateral	Medial	Lateral	Medial	Lateral
Walking	Dominant muscle(s) contributions (%)	SM 18.6 $\pm$ 0.6 VM 16.7 $\pm$ 0.6	BFL 17.4 $\pm$ 0.7 VL 15.3 $\pm$ 0.7	MG 28.9 $\pm$ 0.06	LG 19 $\pm$ 0.8	MG 32.3 $\pm$ 0.7 LG 20.3 $\pm$ 0.7
	TFJ contact loading (BW)	1.39 $\pm$ 0.12	0.90 $\pm$ 0.11	1.14 $\pm$ 0.05	0.60 $\pm$ 0.05	1.06 $\pm$ 0.04 0.69 $\pm$ 0.04
Running	Dominant muscle(s) contributions (%)	VM 18.5 $\pm$ 0.5	VL 22.6 $\pm$ 0.5%	MG 18.1 $\pm$ 0.5	LG 11.8 $\pm$ 0.5 VL 10.3 $\pm$ 0.5 BFLH 9.8 $\pm$ 0.5	MG 24.3 $\pm$ 0.8 NS
	TFJ contact loading (BW)	4.14 $\pm$ 0.21	2.26 $\pm$ 0.18	2.91 $\pm$ 0.10	1.91 $\pm$ 0.09	0.95 $\pm$ 0.08 1.05 $\pm$ 0.07
Sidestepping	Dominant muscle(s) contributions (%)	VM 22.0 $\pm$ 0.5	VL 17.8 $\pm$ 0.5	MG 23.3 $\pm$ 0.8	NS	MG 36.0 $\pm$ 0.16 NS
	TFJ contact loading (BW)	3.60 $\pm$ 0.28	3.24 $\pm$ 0.24	2.36 $\pm$ 0.13	3.05 $\pm$ 0.11	0.59 $\pm$ 0.11 1.66 $\pm$ 0.10

Table 2. Between gait tasks differences in individual relative muscle contribution to medial and lateral TFJ contact loading during each phase of stance. Where NSD is no significant difference, W is walking, R is running, S is sidestepping, * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.

	Weight acceptance		Mid-stance		Push-off	
	Medial	Lateral	Medial	Lateral	Medial	Lateral
RF	W > R***	W > R***	R > W*** S > R***	NSD	S > R***	NSD
VI	R > W*	R > S***	R > W*** S > R***	NSD	R > W** S > R***	R > W***
VM	NSD	W > R***	R > W*** S > R***	NSD	R > W** S > R***	R > W***
VL	R > W**	R > W*** R > S**	R > W*** S > R***	NSD	R > W** S > R***	R > W***
SM	W > R***	W > R***	R > W**	R > S*	R > W***	R > W*** R > S***
ST	W > R***	W > R*** R > S*	R > W**	R > S***	R > W***	R > W*** R > S***
BFLH	W > R***	W > R***	NSD	NSD	R > W**	R > W*** R > S***
BFSH	W > R***	W > R***	NSD	NSD	NSD	NSD
MG	NSD	W > R*** R > S***	W > R***	NSD	W > R* S > R*	W > R*
LG	W > R***	R > S**	W > R*** S > R*	NSD	W > R*** S > R***	W > R***
TFL	W > R***	W > R***	NSD	NSD	NSD	NSD