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The effect of gait modification on the external knee adduction moment is reference frame dependent

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Abstract

Background. This study investigated the extent to which reference frame convention affects the interpretation of how gait modification alters the external knee adduction moment.

Methods. Data were collected from a single male able-bodied subject performing three gait tasks: normal, toe out and medial thrust. The net external moment vector at the knee was expressed in five alternative reference frames: the femur anatomical frame, the proximal tibia anatomical frame, the distal tibia anatomical frame, the laboratory frame and a non-orthogonal knee joint coordinate system. For each reference frame, the knee adduction moment was taken as the component about the frame's anteroposterior axis.

Findings. Gait modification and selected reference frame both influenced the calculated knee adduction moment. Furthermore, these two effects were interactive, with the magnitude of the changes in the knee adduction moment produced by toe out and medial thrust gait being highly dependent on selected reference frame.

Interpretation. Choice of reference frame for calculating the external knee adduction moment is therefore an important consideration for studies investigating the relative effectiveness of interventions such as gait modification.

Keywords: Gait; Knee; Joint moment; Reference frame

1. Introduction

Knee joint osteoarthritis is a prevalent condition (Felson et al., 1987) that commonly involves the medial compartment (Ledingham et al., 1993). It has been demonstrated that during gait substantially higher loads are transferred through the medial compartment compared to the lateral (Zhao et al., 2007a). The external knee adduction moment can provide an approximation of the medial to lateral load distribution (Schipplein and Andriacchi, 1991; Zhao et al., 2007b). A higher knee adduction moment during gait has been related to increased osteoarthritis disease severity (Sharma et al., 1998), an increased risk of structural progression (Miyazaki et al., 2002) and the presence of knee pain in individuals with radiographic evidence of osteoarthritis (Thorp et al., 2007). Strategies to reduce the knee adduction moment during gait are therefore required.

Gait modification is a potential practical and clinically applicable strategy. Several gait modifications have been shown to influence the knee adduction moment. These include barefoot gait (Shakoor and Block, 2006), reduced gait speed (Mundermann et al., 2004), toe out gait (Guo

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et al., 2007; Lin et al., 2001; Zhao et al., 2007b), medial thrust gait (Fregly et al., 2007) and increased mediolateral trunk sway gait (Mundermann et al., 2008). Unfortunately, it is difficult to compare the relative effect of different gait modifications on the knee adduction moment, since inconsistent reference frame conventions have been adopted. For example, Fregly et al. (2007) used a tibial reference frame, whereby the anteroposterior axis was perpendicular to a plane defined by the knee joint centre and the bimalleolar axis. Guo et al. (2007) also used a tibial reference frame, but defined the anteroposterior axis to be perpendicular to a 'plane of best fit' between the medial and lateral femoral condyles and malleoli. Finally, other studies (Mundermann et al., 2008, 2004; Shakoor and Block, 2006) used a 'pseudo-anatomical' tibial reference frame, whereby the mediolateral axis was perpendicular to the plane of progression and the anteroposterior and longitudinal axes rotated in this plane with the tibia. This issue is important, as the knee adduction moment during normal gait has been shown to be sensitive to reference frame convention (Manal et al., 2002; Schache and Baker, 2007). The aim of this study was therefore to demonstrate that the effect of gait modification on the knee adduction moment is reference frame dependent.

2. Methods

2.1. Data collection

A single male able-bodied subject, with a height of 180.5 cm, body mass of 64.0 kg, age 26.6 years and knee varus alignment of 5°, was voluntarily recruited. Institutional ethical approval was obtained prior to commencement. Five trials of three different gait tasks were performed at a self-selected speed: normal gait (1.49 ± 0.05 m/s); toe out gait (1.58 ± 0.04 m/s) and medial thrust gait (1.43 ± 0.05 m/s). For toe out gait, the subject walked with an increased external foot progression angle. For medial thrust gait, the subject walked with slight knee flexion and medialisation of the stance leg knee. This gait modification was achieved by having the subject focus on "rubbing the insides of the knees together". The subject practiced until capable of performing both gait modifications satisfactorily.

Ground reaction force (GRF) and kinematic data were collected during each gait trial. Three AMTI force-plates (Advanced Mechanical Technology Inc., Watertown, MA, USA) were used to capture GRF data. Kinematic data were acquired using a three-dimensional motion analysis system (VICON 512, Oxford Metrics, Oxford, UK) with eight cameras sampling at 120 Hz. Markers (14 mm diameter) mounted on the pelvis and left lower limb (Table 1) were used to obtain the three-dimensional pose of the body segments of interest. Technical frame definitions are outlined in Table 2. Given the potential arbitrary relationship between the defined technical frames and the bony anatomy, static trials were performed to calibrate relevant anatomical landmarks. Anatomical frame (AF) definitions are outlined in Table 3. The knee joint flexion–extension axis was defined using a dynamic optimisation procedure (Schache et al., 2006).

A systematic process was followed to define the AFs prior to commencing gait data collection. First, a static calibration trial was captured with all markers in situ. Second, the orientation of the mediolateral (y) axis of the femoral AF was adjusted so that it corresponded to an optimal estimate of the functional knee joint flexion–extension axis (Schache et al., 2006). This was achieved using a dynamic calibration trial. The subject stood on the right leg and flexed the left shank about the knee to approximately 90°

Table 1
Specific marker locations and orientations

Static and dynamic trials	
LASIS (RASIS)	Anterior to left (and right) anterior superior iliac spine (ASIS) lying in plane containing left and right ASIS and the mid-point between both posterior superior iliac spines (PSIS)
SACR	Posterior to the mid-point between both PSISs lying in plane containing left and right ASISs and the mid-point between both PSISs
TH1	Anterior and middle aspect of left thigh
TH2	Anterior and distal aspect of left thigh
TH3	Lateral and distal aspect of left thigh
SH1	Anteromedial and proximal aspect of left shank
SH2	Anteromedial and distal aspect of left shank
SH3	Lateral and distal aspect of left shank
ANK	Left lateral malleolus aligned with bimalleolar axis
CAL	Bisection of the posterior aspect of the left calcaneum
MID	Left medial midfoot over the distal and dorsomedial aspect of the navicular
LATMID	Left lateral midfoot over the dorsal and distal aspect of the cuboid
Static anatomical landmark calibration trial only	
MFE	Most prominent palpable aspect of left medial femoral epicondyle
LFE	Most prominent palpable aspect of left lateral femoral epicondyle
$TH3^{ROT}$	Virtual point, defined as rotated position of TH3 marker (see text for further explanation)
MED	Left medial malleolus aligned with bimalleolar axis
TOE	Dorsal surface of the left distal forefoot at the mid-point between the 2nd and 3rd metatarsophalangeal joints

Table 2
Technical frame definitions

Pelvis	
Origin	Mid-point between LASIS and RASIS markers
Mediolateral (y) axis	In direction from RASIS to LASIS markers
Anterior-posterior (x) axis	Perpendicular to mediolateral (y) axis in plane containing LASIS, RASIS, SACR markers
Vertical (z) axis	Mutual perpendicular to other two axes
Thigh	
Origin	TH2 marker
Anterior-posterior (x) axis	In direction from TH3 marker to TH2 marker
Mediolateral (y) axis	Perpendicular to anterior–posterior (x) axis in plane containing TH1, TH2 and TH3 markers
Vertical (z) axis	Mutual perpendicular to other two axes
Shank	
Origin	SH2 marker
Vertical (z) axis	In direction from SH2 marker to SH1 marker
Mediolateral (y) axis	Perpendicular to vertical (z) axis in plane containing SH1, SH2, SH3 markers
Anterior–posterior (x) axis	Mutual perpendicular to other two axes
Foot	
Origin	CAL marker
Anterior–posterior (x) axis	In direction from CAL marker to LATMID marker
Mediolateral (y) axis	Perpendicular to anterior–posterior (x) axis in plane containing CAL, LATMID and MID markers
Vertical (z) axis	Mutual perpendicular to other two axes

before returning to full extension. The mediolateral (y) axis of the femoral AF was rotated about the defined vertical (z) axis (knee joint centre to hip joint centre) by an amount (angle θ) necessary to minimise the variance in the knee varus–valgus kinematic profile.

2.2. Data processing

Coordinate data were filtered using Woltring's generalised cross-validated quintic smoothing spline (Woltring, 1986) with a predicted mean-squared error of 15 mm. Temporal events during gait were defined from GRF data. Angular data were calculated using a joint coordinate system (JCS) approach. The JCS for the knee was consistent with that proposed by Grood and Suntay (1983). The JCS used to describe the orientation of the foot with respect to the laboratory frame was as follows: the mediolateral (y) axis corresponded to laboratory (y) axis, the anteroposterior (x) axis was fixed in the foot and the vertical (z) axis was the mutual perpendicular (Baker, 2003). External lower limb joint moments were calculated using a standard inverse dynamics approach, where each joint possessed 6 degrees of freedom and inertial parameter values were estimated as per de Leva (1996).

Knee joint moments were expressed in five different reference frames: the femur AF, the proximal tibia AF, the distal tibia AF, the laboratory frame and the knee JCS. For each reference frame, several additional parameters were calculated. These included the frontal plane projection of the GRF (GRF^{FP}) and its associated lever arm, as well as the knee adduction angular impulse. The GRF^{FP} was calculated as the resultant force vector of the vertical and mediolateral components of the GRF, whilst the frontal plane lever arm was calculated as the perpendicular distance between the GRF^{FP} and the knee joint centre. The knee adduction angular impulse was calculated by integrating the stance phase adduction (positive) portion of the knee adduction moment. From these data, the following discrete point parameters were extracted:

1. The magnitude of the first peak in the external knee adduction moment (Nm/kg);
2. The magnitude of the GRF^{FP} at the time of the first peak in the external knee adduction moment (N);
3. The magnitude of the GRF^{FP} lever arm at the time of the first peak in the external knee adduction moment (cm);
4. The magnitude of the second peak in the external knee adduction moment (Nm/kg);
5. The magnitude of the GRF^{FP} at the time of the second peak in the external knee adduction moment (N);
6. The magnitude of the GRF^{FP} lever arm at the time of the second peak in the external knee adduction moment (cm);
7. The net external knee adduction angular impulse (Nm s/kg);
8. The magnitude of the peak stance external knee flexion moment (Nm/kg).

Each of the discrete point parameters analysed were averaged across the five trials to report mean and standard deviation values for a given reference frame and gait task.

3. Results

Both toe out and medial thrust gait altered lower limb kinematics. Toe out gait increased external foot progression by 11° compared to normal gait, with minimal change in knee flexion–extension. Medial thrust gait increased stance phase knee flexion, with foot progression remaining

Table 3
Anatomical frame (AF) definitions

Pelvis	
Origin	Mid-point between LASIS and RASIS markers
Mediolateral (y) axis	In direction from RASIS to LASIS markers
Anterior–posterior (x) axis	Perpendicular to mediolateral (y) axis in plane containing LASIS, RASIS, SACR markers
Vertical (z) axis	Mutual perpendicular to other two axes
Virtual point	Hip joint centre defined relative to pelvic anatomical frame as per Harrington et al. (2007)
Femur	
Origin	Knee joint centre defined as mid-point between LFE and MFE markers
Vertical (z) axis	In direction from knee joint centre to hip joint centre
Mediolateral (y) axis	Perpendicular to vertical (z) axis in plane containing knee joint centre, hip joint centre, and TH3 marker, rotated by angle θ about vertical (z) axis, whereby θ represents degree of rotation required to minimise variance in dynamic knee varus–valgus kinematic profile
Anterior–posterior (x) axis	Mutual perpendicular to other two axes
Virtual points	Knee joint centre and TH3$^{\mathrm{ROT}}$ as defined above
Proximal tibia	
Origin	Ankle joint centre defined as mid-point between ANK and MED markers
Vertical (z) axis	In direction from ankle joint centre to knee joint centre location
Mediolateral (y) axis	Perpendicular to vertical (z) axis and parallel to femur mediolateral (y) axis when in anatomical landmark calibration configuration
Anterior–posterior (x) axis	Mutual perpendicular to other two axes
Virtual point	Ankle joint centre as defined above
Distal tibia	
Origin	Ankle joint centre defined as mid-point between ANK and MED markers
Vertical (z) axis	In direction from ankle joint centre to knee joint centre location
Mediolateral (y) axis	Perpendicular to vertical (z) axis in plane containing knee joint centre, MED and ANK markers
Anterior–posterior (x) axis	Mutual perpendicular to other two axes
Virtual point	AJC as defined above
Foot	
Origin	Ankle joint centre defined as mid-point between ANK and MED markers
Vertical (z) axis	Parallel to the laboratory (z) axis when in anatomical landmark calibration configuration
Anterior–posterior (x) axis	Perpendicular to vertical (z) axis and parallel (in horizontal plane of laboratory frame) to a line connecting CAL and TOE markers
Mediolateral (y) axis	Mutual perpendicular to other two axes
Virtual point	Ankle joint centre as defined above

neutral (Fig. 1). The knee adduction moment was sensitive to both gait modifications (Table 4; Fig. 2). Toe out gait influenced the second peak more than the first. The opposite occurred for medial thrust gait. Toe out gait increased the first peak but reduced the second, whilst medial thrust gait reduced both peaks. Both gait modifications influenced the knee adduction moment primarily by changing the magnitude of the GRF$^{\mathrm{FP}}$ lever arm. The knee adduction angular impulse was less sensitive to gait modification than the knee adduction moment peaks (Table 4). Medial thrust gait was associated with greater change in the knee adduction angular impulse than was toe out gait. Both gait modifications increased the peak stance knee flexor moment, with the increase being greater for medial thrust gait (Table 4).

The knee adduction moment was sensitive to alternate reference frames (Table 4; Fig. 2). For the femur AF, knee JCS and proximal tibia AF, the magnitude of the first peak exceeded the second. In contrast, for the distal tibia AF and the laboratory frame, the magnitude of the first peak was similar to the second. These differences were primarily attributable to changes in the magnitude of the GRF$^{\mathrm{FP}}$ lever arm across reference frames (Table 4).

An interaction between gait modification and reference frame effects was evident (Table 4; Fig. 2). The effect of gait modification on the knee adduction angular impulse was not systematic across reference frames. For toe out gait, there was little change in the knee adduction angular impulse for the femur AF, knee JCS, proximal tibia AF and laboratory frame, but a decrease of 12.9% for the distal tibia AF. For medial thrust gait, there was a small increase in the knee adduction angular impulse for the femur AF, knee JCS and proximal tibia AF, but an appreciable decrease for the distal tibia AF and laboratory frame of 29.7% and 22.6%, respectively. Whilst the effect of gait modification on the knee adduction moment peaks was systematic across reference frames, the effect size varied considerably. For toe out gait, the increase in the first peak ranged from 0.4% (distal tibia AF) to 29.4% (laboratory frame), whilst the reduction in the second peak ranged from 22.9% (distal tibia AF) to 34.0% (femur AF). For medial thrust gait, the reduction in the first peak ranged from 2.4% (proximal tibia AF) to 43.8% (distal tibia AF), whilst the reduction in the second peak ranged from 7.8% (femur AF & proximal tibia AF) to 17.3% (distal tibia AF).

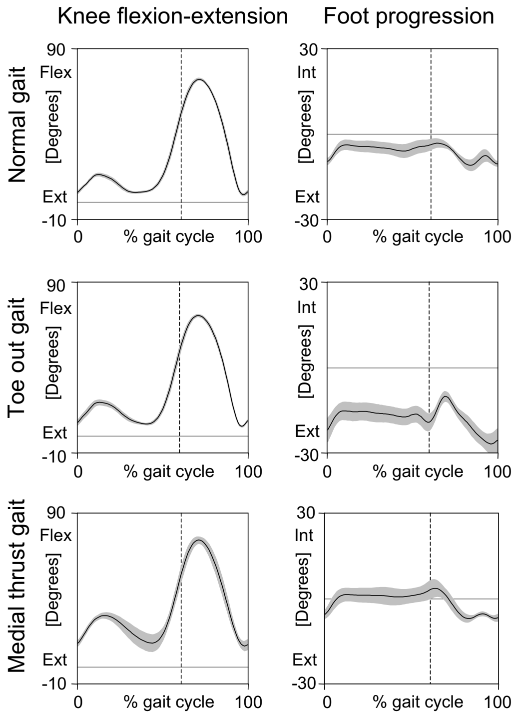

Fig. 1. Sagittal plane knee (flexion/extension) and transverse plane foot (internal/external foot progression or toe in/out) kinematics during normal, toe out and medial thrust gait. The grey shading represents the inter-trial standard deviation. The dashed vertical lines indicate toe off.

4. Discussion

The primary goal of this study was to demonstrate that choice of reference frame has the potential to significantly influence the interpretation of how gait modification affects the knee adduction moment. A single subject was therefore considered sufficient. In fact, this issue could have been demonstrated using a purely mathematical approach. However, by analyzing experimental data taken from a subject before and after adopting a recognised strategy for reducing the knee adduction moment, the issue has been demonstrated in a more clinically appropriate context.

Results from the current study concur with previous research. When considering the effect of gait modification on the knee adduction moment, it has been shown that toe out gait reduces the second peak (Guo et al., 2007; Lin et al., 2001), whilst medial thrust gait reduces both peaks (Fregly et al., 2007). These findings are consistent with those from the current study (Table 4; Fig. 2). When considering the effect of different reference frames on the knee adduction moment for normal gait, the magnitude of the first peak has been shown to be significantly reduced for: (a) the laboratory frame in comparison to the femur AF, proximal tibia AF and knee JCS and; (b) the femur AF in comparison to the knee JCS (Schache and Baker, 2007). Furthermore, the magnitude of the first peak has been found to be significantly increased for the proximal tibia AF compared to the distal tibia AF (Manal et al., 2002). These findings are also consistent with those from the current study (Table 4; Fig. 2).

It has been suggested that toe out and medial thrust gait influence the knee adduction moment by decreasing the lever arm of the GRF vector (applied at the centre of pressure) about the knee joint centre (Fregly et al., 2007; Guo et al., 2007). Results from the current study confirm this claim. Both medial thrust and toe out gait were found to primarily achieve their effect by altering the magnitude of the $\mathrm{GRF}^{\mathrm{FP}}$ lever arm rather than the magnitude of the $\mathrm{GRF}^{\mathrm{FP}}$ itself (Table 4). This result is in agreement with that recently reported by Jenkyn et al. (2008) who measured the external knee adduction moment on 180 patients with knee osteoarthritis whilst walking with a self-selected degree of toe out. The biomechanical effect of toe out gait for each patient was mathematically simulated by comparing the magnitude of the $\mathrm{GRF}^{\mathrm{FP}}$ lever arm and the knee adduction moment when expressed in a tibial reference frame (simulated toe out) and a laboratory reference frame (simulated no-toe out). Toe out gait was found to produce a 22.9% reduction in the $\mathrm{GRF}^{\mathrm{FP}}$ lever arm at the second peak of the knee adduction moment, which is remarkably consistent with the current study where equivalent reductions of 24.6% and 18.8% were found for the proximal and distal tibia AF's respectively (Table 4).

The findings from the current study are of clinical significance. Different reference frames can lead to contrasting interpretations regarding the potential effectiveness of a given gait modification. For example, Fregly et al. (2007) found medial thrust gait to produce reductions in the knee adduction moment of up to 50% and 55% for the first and second peaks, respectively. In the current study, medial thrust gait was found to produce reductions of a similar magnitude (at least for the first peak) only when the knee adduction moment was expressed in the distal tibia AF or the laboratory frame. If the knee adduction moment was expressed in one of the other three possible reference frames, then medial thrust gait was found to be far less effective, with reductions ranging from 2.4% to 13.6% and 7.8% to 8.6% for the first and second peaks, respectively (Table 4). In a similar manner, toe out gait could be interpreted to have no effect on the first peak (distal tibia AF) or actually cause an undesirable 29.4% increase in the first peak (laboratory frame). The degree to which toe out gait reduced the second peak also varied by up to 11.1% for different reference frames (Table 4). Choice of reference frame is therefore an important consideration when determining the relative effectiveness of gait modifications on the knee adduction moment.

The knee adduction moment is of most clinical relevance for a population with medial compartment knee joint osteoarthritis. It is therefore acknowledged that the results of this study are limited to the young able-bodied adult male subject investigated. However, this was not considered to be a major limitation for two reasons. First, by testing a young and lean (BMI 19.8) subject, errors due to soft tissue artefact were minimised. Second, the main outcomes

Table 4
Mean (SD) values for the discrete point parameters across the various reference frames and gait tasks

Parameter	Gait task	Reference frame									
		Femur	% Δ	Knee JCS	% Δ	Proximal tibia	% Δ	Distal tibia	% Δ	Laboratory	% Δ
1st peak KAM (Nm/kg)	Normal	0.86 (0.05)	–	0.89 (0.06)	–	0.89 (0.06)	–	0.56 (0.03)	–	0.69 (0.06)	–
	Toe out	0.97 (0.07)	+13.5	1.01 (0.07)	+13.2	0.99 (0.05)	+11.2	0.56 (0.07)	+0.4	0.90 (0.08)	+29.4
	Medial thrust	0.74 (0.05)	−13.6	0.80 (0.05)	−10.5	0.87 (0.04)	−2.4	0.32 (0.03)	−43.8	0.41 (0.06)	−41.3
GRF^{FP} at 1st peak KAM (N)	Normal	772.37 (55.48)	–	772.37 (55.48)	–	765.11 (56.72)	–	741.39 (77.23)	–	761.31 (56.81)	–
	Toe out	769.70 (19.52)	−0.4	769.70 (19.52)	−0.4	762.14 (25.58)	−0.4	765.52 (23.10)	+3.3	770.36 (22.83)	+1.2
	Medial thrust	789.54 (23.89)	+2.2	789.54 (23.89)	+2.2	779.76 (24.14)	+1.9	738.91 (60.21)	−0.3	740.07 (60.00)	−2.8
LA at 1st peak KAM (cm)	Normal	7.15 (0.16)	–	7.46 (0.14)	–	7.35 (0.43)	–	4.79 (0.20)	–	5.83 (0.23)	–
	Toe out	8.12 (0.71)	+13.5	8.44 (0.72)	+13.1	8.41 (0.59)	+14.5	4.64 (0.65)	−3.0	7.50 (0.72)	+28.7
	Medial thrust	6.08 (0.37)	−14.9	6.55 (0.34)	−12.2	7.27 (0.26)	−1.1	2.74 (0.39)	−42.7	3.55 (0.58)	−39.1
2nd peak KAM (Nm/kg)	Normal	0.56 (0.05)	–	0.53 (0.05)	–	0.53 (0.05)	–	0.52 (0.05)	–	0.56 (0.05)	–
	Toe out	0.37 (0.02)	−34.0	0.36 (0.02)	−32.9	0.37 (0.01)	−30.6	0.40 (0.02)	−22.9	0.38 (0.01)	−31.7
	Medial thrust	0.52 (0.02)	−7.8	0.49 (0.02)	−8.3	0.49 (0.02)	−7.8	0.43 (0.03)	−17.3	0.49 (0.03)	−12.6
GRF^{FP} at 2nd peak KAM (N)	Normal	677.07 (7.66)	–	677.07 (7.66)	–	668.04 (7.19)	–	694.26 (10.64)	–	691.46 (11.40)	–
	Toe out	644.03 (26.02)	−4.9	638.90 (28.54)	−5.6	627.98 (21.02)	−6.0	652.29 (20.63)	−6.1	644.89 (35.04)	−6.7
	Medial thrust	662.88 (11.02)	−2.1	662.88 (11.02)	−2.1	655.51 (11.66)	−1.9	671.33 (14.97)	−3.3	675.97 (13.70)	−2.2
LA at 2nd peak KAM (cm)	Normal	5.27 (0.52)	–	4.99 (0.49)	–	5.03 (0.50)	–	4.90 (0.41)	–	5.22 (0.55)	–
	Toe out	3.71 (0.32)	−29.6	3.60 (0.30)	−27.9	3.79 (0.22)	−24.6	3.97 (0.16)	−18.9	3.84 (0.28)	−26.4
	Medial thrust	5.08 (0.26)	−3.7	4.76 (0.20)	−4.5	4.85 (0.28)	−3.6	4.21 (0.21)	−14.0	4.75 (0.16)	−9.1
Net KAAI (Nm s/kg)	Normal	0.24 (0.01)	–	0.24 (0.01)	–	0.24 (0.01)	–	0.21 (0.01)	–	0.23 (0.01)	–
	Toe out	0.24 (0.01)	0	0.24 (0.01)	+0.4	0.24 (0.01)	+0.4	0.18 (0.01)	−12.9	0.23 (0.01)	+1.7
	Medial thrust	0.25 (0.01)	+2.9	0.25 (0.01)	+4.2	0.26 (0.01)	+10.0	0.15 (0.01)	−29.7	0.18 (0.01)	−22.6
Peak stance KFM (Nm/kg)	Normal	0.62 (0.03)	–	0.62 (0.03)	–	0.60 (0.03)	–	0.93 (0.05)	–	0.84 (0.04)	–
	Toe out	0.78 (0.09)	+26.8	0.78 (0.09)	+26.8	0.79 (0.09)	+30.6	1.14 (0.08)	+21.8	0.90 (0.08)	+7.3
	Medial thrust	1.21 (0.08)	+96.8	1.21 (0.08)	+96.8	1.16 (0.08)	+92.2	1.42 (0.08)	+51.9	1.40 (0.09)	+67.0

% Δ Percentage change from normal gait; KAM External knee adduction moment; GRF^{FP} Frontal plane projection of the ground reaction force; LA Lever arm of the GRF^{FP}; KAAI External knee adduction angular impulse; KFM external knee flexion moment.

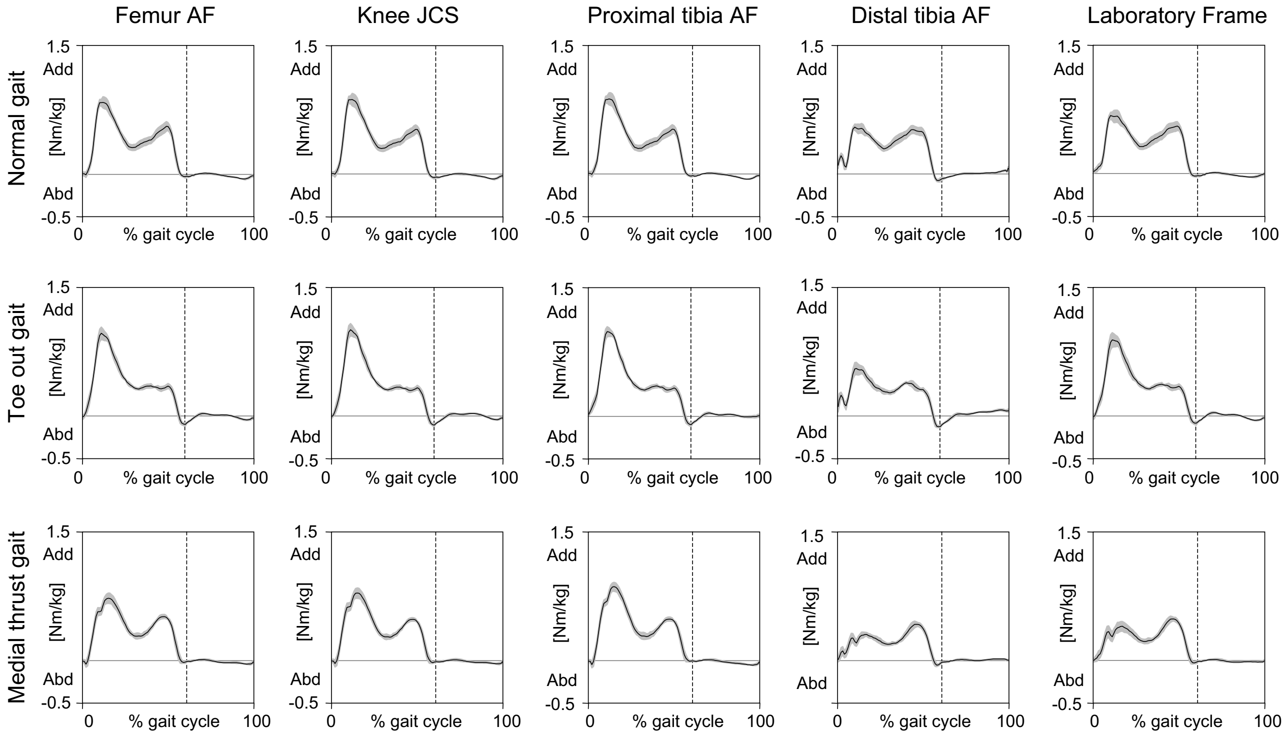

Fig. 2. The external knee adduction moment (expressed in the five alternative reference frames) during normal, toe out and medial thrust gait. The grey shading represents the inter-trial standard deviation. The dashed vertical lines indicate toe off.

from this study are not likely to be subject and/or disease specific.

It is worth noting that all reference frames evaluated in this study are mathematically correct. The question is which one is most appropriate for calculating the knee adduction moment. Several factors warrant consideration in this context. First, which convention is least susceptible to soft tissue artefact? In this regard, the laboratory frame or distal tibia AF appear most favourable, as thigh markers are associated with increased soft tissue artefact (Cappozzo et al., 1996; Reinschmidt et al., 1997). Second, which convention is most anatomically appropriate? In this regard, Fisher et al. (2007) have argued against the use of the femoral AF as it does not remain stationary with respect to the points of contact at the knee joint. Other studies have recommended the non-orthogonal JCS (Fujie et al., 1996; Schache and Baker, 2007) so as to obtain knee joint moments about axes that are consistent with the ISB recommendations for reporting of knee joint kinematics (Wu and Cavanagh, 1995). Finally, which convention best predicts the clinical outcome of interest? In the context of medial compartment knee joint osteoarthritis, the knee adduction moment is used as surrogate measure of medial compartment contact force, which in turn is assumed to be a causative factor for disease development and progression. Thus, the ideal convention would be that which best reflects changes in medial compartment contact force. Whilst it has been shown that the profile over the gait cycle for the knee adduction moment in a distal tibia AF is highly correlated to that for medial compartment contact force (Zhao et al., 2007b), it is not known whether the same is true for other possible reference frames. Furthermore, it is not known which reference frame produces changes in the knee adduction moment that are consistent with changes that occur in medial compartment contact force for interventions such as gait modification.

It is important that researchers and clinicians recognise the potential for choice of reference frame to significantly influence the interpretation of how interventions such as gait modification affect the knee adduction moment. It is difficult to recommend a single ‘ideal’ solution that adequately fulfills all of the above-mentioned factors, as there currently exists insufficient published data upon which to base such a conclusion. Researchers and clinicians therefore need to appreciate the various alternatives for resolving the net moment vector and make careful decisions about which approach is likely to be most appropriate for their given application. Future studies investigating methods to improve the experimental validity of the reference frames, especially those which necessitate the definition of a femoral AF, as well as determining which reference frame represents the best clinical correlate, would be of particular value.

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