Muscular co-contraction is related to varus thrust in patients with knee osteoarthritis

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Abstract

Background: Patients with knee osteoarthritis often present with varus thrust and muscular co-contraction during gait. It is unclear if these adaptations are related. The objective was to examine the relationship between muscle co-contraction and varus thrust during gait in patients with knee osteoarthritis and to determine if these relationships are modulated by disease severity or history of knee ligament rupture.

Methods: Participants (n=42, 23 women, mean age 58 years) with knee osteoarthritis completed gait trials at self-selected speeds. Varus thrust was measured with an eight camera motion capture system sampled at 100 Hz. Co-contraction ratios were measured with surface electromyography sampled at 2000 Hz over the quadriceps, hamstrings, and gastrocnemius. Disease severity was measured on radiographs and history of anterior cruciate ligament rupture was confirmed on magnetic resonance imaging. Linear regression analyses examined the relationship between varus thrust and co-contraction ratios after controlling for radiographic disease severity and history of anterior cruciate ligament rupture.

Findings: Higher vastus lateralis–lateral hamstring (b=0.081, $P<0.001$; $R^2=0.353$) and vastus medialis–medial hamstring (b=0.063, $P=0.028$; $R^2=0.168$) co-contraction ratios were associated with greater varus thrust. Quadriceps-gastrocnemius co-contractions ratios were not related to varus thrust ($P>0.05$). Radiographic disease severity or history of anterior cruciate ligament injury did not significantly contribute to regression models.

Interpretation: Greater quadriceps-hamstring co-contraction is associated with greater varus thrust in patients with knee osteoarthritis. Potential explanations include increased

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co-contraction may provide stability or there is a proprioceptive reflex that is independent of any stabilizing role. Research is needed to test these hypotheses.

Key Words: knee osteoarthritis; gait; varus thrust; electromyography; co-contraction

1. Introduction

Knee osteoarthritis (OA) affects 16% of adults over 45 years of age, making it one of the most prevalent musculoskeletal conditions (Jordan et al., 2007). Knee OA often results in abnormal gait patterns compared to healthy adults (Mills et al., 2013a). One such gait abnormality is varus thrust, which is a marked “bowing out” of the knee during weight acceptance and may result from the inability to control the high forces exerted on the medial compartment. Varus thrust occurs in 36.7% of patients with radiographic knee OA (Chang et al., 2010) and it is a risk factor for knee OA progression (Chang et al., 2004; Sharma et al., 2017). Varus thrust has been associated with static knee alignment (Kuroyanagi et al., 2012), pain (Lo et al., 2012), knee adduction moment (Kuroyanagi et al., 2012; Mahmoudian et al., 2016), and disease severity (Chang et al., 2010; Kuroyanagi et al., 2012). Further research is needed to determine the importance of varus thrust, its cause, other disease factors that impact it, and the manner in which the body compensates for this gait abnormality.

Patients with knee OA present with excessive muscular co-contraction during gait (Mills et al., 2013b). This behavior occurs in the both lateral (vastus lateralis-lateral hamstring) and medial (vastus medialis-medial gastrocnemius) muscle pairs (Hubley-Kozey et al., 2009; Lewek et al., 2004; Mills et al., 2013b). It has been hypothesized that muscle co-contraction may help stiffen and stabilize the knee during gait through

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increased compressive forces and joint loading (Brandon et al., 2014; Lewek et al., 2004). Considering muscular co-contraction could stiffen the knee, it might provide a mechanism to limit varus thrust.

Previous studies have not examined the relationship between varus thrust and co-contraction. If a relationship between these gait abnormalities existed, it would provide evidence that co-contraction might play a role in stiffening the joint and not be merely a response to pain or muscle weakness in patients with knee OA. Furthermore, co-contraction could increase joint loading, and may mediate the relationship between varus thrust and OA progression (Chang et al., 2004; Sharma et al., 2017). It is unclear if the relationship between varus thrust and co-contraction would be modulated by disease severity or aetiology. Concerning aetiology, differences in the knee adduction moment during gait and frontal plane static knee alignment have been found between patients with non-traumatic and post-traumatic knee OA (Robbins et al., 2016). This latter group had a history of anterior cruciate ligament (ACL) rupture. Considering that frontal plane mechanics differ between these knee OA subtypes, varus thrust and its relationship to other variables might differ between patients with non-traumatic and post-traumatic knee OA. Previous research has not examined this question. Additionally, the ACL provides stability in the frontal plane and injury to this ligament could impact frontal plane mechanics and potentially varus thrust (Shin et al., 2011).

Therefore, the objective of this study was to examine the relationship between muscle co-contraction and varus thrust during gait in patients with knee OA and to determine if this relationship is modulated by disease severity or history of ACL injury. We hypothesized that greater varus thrust would be related to higher muscle co-

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contraction levels after controlling for disease severity and history of ACL injury in patients with knee OA.

2. Methods

2.1 *Participants*

Participants with knee OA (n=42) were recruited from tertiary hospitals and the local community. They were part of an ongoing longitudinal study examining OA progression in participants with non-traumatic and post-traumatic knee OA. Only baseline data were examined for this cross-sectional analysis. All participants had a diagnosis of knee OA according to clinical criteria from the American College of Rheumatology (Altman et al., 1986). In addition, they had to be between the ages of 40 and 75 years. Exclusion criteria included knee trauma or surgery in the past year, previous joint arthroplasty, inflammatory arthritis, or neurological conditions (e.g. previous stroke). Twenty-three participants had an intact ACL (OA-only group), while 19 participants had a confirmed ACL rupture (n=9) or reconstruction (n=10) based on magnetic resonance imaging analysis (OA-ACL group). Participant demographics and relevant study variables are presented in Table 1. All participants provided written informed consent. The study was approved by the local ethics committee.

2.2 Gait data collection

Kinematic data were acquired using an 8-camera motion capture system (OQUS 300+, Qualisys, Göteborg, Sweden), sampled at 100 Hz, and a previously

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described cluster-based reflective marker set (Collins et al., 2009). Kinetic data were collected with two force plates (BP400600, AMTI Inc., Watertown, USA), embedded in an 8 m walkway, sampled at 2000 Hz. Kinetic data were used to determine gait events (e.g. heel strike). Surface electromyography (EMG) was sampled at 2000 Hz using wireless sensors, each with four dry contact 5 x 1 mm parallel bar silver (99.9%) electrodes (Trigno, Delsys Inc., Natick, USA; common mode rejection ratio >80 db at 60 Hz, band-width 20–450 Hz, signal amplification 1000). Participants changed into tight fitting shorts and a short-sleeved shirt in preparation for a laboratory-based, over ground gait analysis session. EMG sensors were placed over the vastus medialis, vastus lateralis, lateral hamstring, medial hamstring, lateral gastrocnemius, and medial gastrocnemius according to established guidelines (Rutherford et al., 2011). Sensor locations were manually palpated and verified through voluntary contraction. Skin was shaved and cleaned before affixing the electrodes. The cluster-based reflective marker set was then applied according to established guidelines (Collins et al., 2009).

Prior to the gait trials, a static trial was performed, with the participants standing on the force plates, to determine ankle and knee joint centers and body mass. Dynamic calibration trials were then performed, requiring participants to flex/extend and adduct/abduct their hips, to determine hip joint centers (Schwartz and Rozumalski, 2005). For the gait trials, participants were allowed at least four practice trials to get accustomed to the testing environment. They then made at least seven passes over the 8 m long walkway, at a self-selected walking speed. However, only five trials were processed and examined. Additional trials were completed to account for potential data collection errors (e.g. missing markers) and participants were requested to complete

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additional trials if the researchers noted any issues during data collection. All trials were performed barefoot.

After the gait trials, participants completed a series of maximum voluntary isometric contractions (MVIC) which were used to amplitude normalize gait EMG (Rutherford et al., 2011). Most MVIC exercises were completed on an instrumented dynamometer (Cybex Humac Norm, Computer Sports Medicine Inc., Stoughton, USA). Participants performed a practice trial followed by two MVIC trials, separated by 30 seconds, for each exercise. MVIC exercises included: 1) knee extension in sitting with the knee in 45^{o} of flexion; 2) knee flexion in sitting with the knee at 55^{o} of flexion; 3) knee extension in supine with the knee in 15^{o} of flexion; 4) knee flexion in prone with the knee in 55^{o} of flexion; 5) ankle plantarflexion in long sitting with the ankle in neutral; 6) unilateral heel raise on a step.

2.3 *Gait data processing*

Kinematic data for each gait trial were partitioned to 4 steps, labelled, and gap filled using a polynomial spline interpolation function (maximum 10 frames) in Qualisys Track Manager (v2.16, Qualisys, Göteborg, Sweden). Next, data were exported to Visual 3D (v5, C-motion Inc., Germantown, USA). Marker and force plate data were filtered with recursive, low-pass, 4th order Butterworth filters with frequency cuts offs of 8 and 20 Hz respectively. Three-dimensional knee angles were computed based on the joint coordinate system (Grood and Suntay, 1983). Gait speed was determined from markers on the posterior superior iliac spines. Heel strike and toe off gait events were identified by contact with a force plate, while the second occurrence of these events

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were identified using a kinematic based method (Stanhope et al., 1990). Additionally, the end of mid-stance was determined when the heel markers on the left and right feet crossed in the direction of forward progression.

EMG data from gait trials were rectified and linear enveloped using a recursive, low-pass, 4th order Butterworth filter at 6 Hz. EMG data from MVIC trials were rectified and a moving-average window (100 ms) identified the maximum EMG. Gait EMG were then amplitude normalized to MVIC EMG signals (Hubley-Kozey et al., 2013). Finally, data were exported to Matlab (v2017b, The Mathworks Inc., Natick, USA) to compute the main dependent variables in this study using the biomechZoo toolbox (Dixon et al., 2017) and custom scripts.

2.3.1 Varus thrust

Varus thrust was defined as the absolute difference between the knee adduction angle at heel strike and the maximum knee adduction angle between heel strike and the end of mid-stance (Fig. 1) (Hunt et al., 2011; Mahmoudian et al., 2016). Using this approach, some participants had zero varus thrust, as the maximum knee adduction angle occurred at heel-strike. Varus thrust was determined for each gait trial and was averaged over five trials for each participant.

2.3.2 Muscle co-contraction

Four muscle pairs were used to calculate co-contraction ratios: vastus lateralis–lateral hamstring, vastus lateralis–lateral gastrocnemius, vastus medialis–medial hamstring, and vastus medialis–medial gastrocnemius (Hubley-Kozey et al., 2009). Co-

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contraction ratios (CCR) were computed for each muscle pair according to Rudolph et al. (2000) by finding the EMG signal with the lower and higher activation across each data frame (t):

$$CCR(t) = \frac{lower\ EMG(t)}{higher\ EMG\ (t)} \times (lower\ EMG(t) + higher\ EMG(t)) \quad (1)$$

For each trial, the mean of the co-contraction ratio was computed from 100 ms prior to heel strike to maximum knee adduction angle. Co-contraction ratios were determined for each gait trial and were averaged over five trials for each participant.

2.4 Clinical Measures

Participants underwent full length, standing, anterior-posterior radiographs. Radiographic knee OA severity was measured with Kellgren-Lawrence (KL) disease severity scores (Kellgren and Lawrence, 1957). KL scores rate OA disease severity on a five point scale (0=no OA, 1=doubtful, 2=mild, 3=moderate, 4=severe). A measure of knee alignment, the mechanical axis angle (MAA), was calculated as previously described (Specogna et al., 2004) using ImageJ software (National Institutes of Health). Valgus alignment was represented by positive values and varus alignment by negative values.

Participants completed the Intermittent and Constant Osteoarthritis Pain measure to further describe the study sample (Robbins et al., 2014). This is an 11 item measure with subscales for constant and intermittent pain. Only the total score was presented which was converted to a 0-100 score. High scores represent extreme pain.

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2.5 Statistical analysis

Differences in demographic (age, height, body mass, body mass index) and study (gait speed, varus thrust, KL score, MAA, and co-contraction ratios) variables between OA-only and OA-ACL groups were assessed using unpaired t-tests (parametric) or Mann-Whitney tests (non-parametric).

Hypothesis-driven, sequential, forward linear regression analyses were completed to test the hypothesis that varus thrust and muscle co-contractions were associated. Varus thrust was the dependent variable. Predictors were entered in the analyses in the following order: KL score, OA group (OA-only, OA-ACL group), and muscle pair co-contraction ratio. These predictors were forced into the analyses regardless of their significance. Separate analyses were completed for each co-contraction ratio resulting in four regression analyses. Potential interactions between the predictors were explored, including between OA group and co-contraction ratios. Interactions only remained in the final model if they were statistically significant. For each predictor variable, the change in R^2, unstandardized coefficients (b) with 95% confidence intervals, and associated significance levels were reported. The total R^2 was also reported for each analysis. A significance level of $\alpha=0.05$ was used. Assumptions for regression analyses were examined including multicollinearity, homoscedasticity, normality, and linearity. Statistical analyses were performed in SPSS (v24, IBM Corp., Armonk, USA).

3. Results

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There were no differences in demographic (e.g. age) or study (e.g. varus thrust) variables between OA-only and OA-ACL groups (Table 1). Nine participants had varus thrust values less than 1^{o}, including two participants that had values of 0^{o} (Fig. 2). These participants were included in the analyses. Four participants did not have five available gait trials because sufficient data before heel strike were not present to determine co-contraction ratios. These participants still had available data (1 to 4 trials) and thus were included in analyses, although with fewer trials. There were also missing co-contraction ratios for some muscle pairs in other participants due to data collection errors. One participant refused to undergo radiographs and thus did not have KL scores or MAA. The number of participants in each analysis is provided in Table 2.

The vastus lateralis-lateral hamstring co-contraction ratio accounted for a significant amount of variance in varus thrust after controlling for KL scores and OA group (OA-only, OA-ACL) (Table 2). Higher varus thrust was associated with higher vastus lateralis-lateral hamstring co-contraction ratios (Fig. 2). The final model accounted for a significant amount of the explained variance in varus thrust (R^2=0.353, P=0.001).

Likewise, vastus medialis-medial hamstring co-contraction ratio accounted for a significant amount of variance in varus thrust after controlling for KL scores and OA group (Table 2). Higher varus thrust was associated with higher vastus medialis-medial hamstring co-contraction ratios (Fig. 2). However, the final model (KL scores, OA group, vastus medialis-medial hamstring co-contraction ratio) did not explain a significant amount of variance in varus thrust (R^2=0.168, P=0.082).

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For both vastus lateralis-lateral hamstring and vastus medialis-medial hamstring co-contraction ratios, outliers were evident (Fig. 2). Removal of outliers (co-contraction >60) in a post-hoc analysis did not change the interpretation of the results for either muscle pair (i.e. results remained significant). However, the strength of the relationship between the vastus lateralis-lateral hamstring co-contraction ratio and varus thrust did decrease, although it remained significant (coefficient: B=0.081, *P*=0.048; overall model: R^2=0.123, *P*=0.210).

The remaining co-contraction ratios (vastus lateralis-lateral gastrocnemius and vastus medialis-medial gastrocnemius) did not significantly explain the variance in varus thrust (Table 2). Unstandardized regression coefficients for the KL scores and OA group were not statistically significant for any regression analysis (Table 2). Also, no significant interactions existed between co-contraction ratios and either KL score or OA group (results not shown). An examination of the residuals and collinearity statistics confirmed that all regression assumptions were met.

4. Discussion

The current study demonstrated that varus thrust during gait was significantly related to both vastus lateralis-lateral hamstring and vastus medialis-medial hamstring co-contraction ratios, after controlling for disease severity and history of ACL rupture. Varus thrust was not related to quadriceps-gastrocnemius co-contraction ratios. To our knowledge, this is the first study to establish a link between neuromuscular activation, specifically co-contraction of muscle pairs, and varus thrust. These findings suggest that co-contraction of muscle pairs might be intended to provide a stabilizing force against

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varus thrust; however, causation cannot be confirmed with the current research design. Considering that greater varus thrust was related to greater co-contraction, this neuromuscular adaptation might not provide sufficient force to limit this excessive movement.

There are several hypotheses that might explain the findings. Firstly, muscular co-contraction may represent an attempt to stiffen the knee, minimize varus thrust, and provide stability during the loading phase of gait. Other researchers have proposed a similar hypothesis when attempting to explain increases in quadriceps and hamstring muscle activation in patients with knee OA (Brandon et al., 2014). Another study demonstrated that a change in medial compartment joint space with knee stress tests was related to vastus medialis-medial gastrocnemius co-contraction, providing further evidence that co-contraction might be an attempt to stabilize the joint (Lewek et al., 2004). Alternatively, there might be a proprioceptive reflex that occurs with knee adduction which increases muscle activation and this could be independent of any stabilizing role. Finally, perhaps the relationship between co-contraction and varus thrust is spurious, and a third factor (e.g. pain response) might relate to both of these gait abnormalities. Regardless, patients with knee OA that had greater varus thrust had greater muscle co-contraction. This co-contraction likely increases knee loading, and prolonged co-contraction has been shown to relate to cartilage loss over 12 months in patients with knee OA (Brandon et al., 2014; Hodges et al., 2016). Therefore, co-contraction may not represent an appropriate long-term strategy.

The mean varus thrust for the current sample (mean=2.99^{o}) was similar to a previous study of patients with mild (mean=2.4^{o}) and moderate (mean=2.8^{o}) knee OA;

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however, patients with severe knee OA from the previous study had higher varus thrust values (mean=7.2^{o}) (Kuroyanagi et al., 2012). Additionally, varus thrust did not relate to disease severity and history of ACL rupture. Two studies have shown that disease severity is related to varus thrust (Chang et al., 2010; Kuroyanagi et al., 2012), while another study found no relationship (Mahmoudian et al., 2016). Studies that found a significant relationship had a greater proportion of patients with severe radiographic knee OA and thus the study sample might explain the findings (Chang et al., 2010; Kuroyanagi et al., 2012). Also, there were differences in methods to measure varus thrust between studies, which might account for the findings. Here, the full three-dimensional kinematic method (Mahmoudian et al., 2016) was favored over both the visual, clinical approach (Chang et al., 2010) or a two-dimensional calculation (Kuroyanagi et al., 2012). Furthermore, varus thrust did not differ between OA-only and OA-ACL groups. Previous studies have not compared varus thrust between similar groups; however, a previous study did demonstrate that varus thrust did not relate to self-reported history of knee trauma in patients with knee OA (Chang et al., 2010). Research should examine the relationship between varus thrust and other OA disease characteristics in order to understand how varus thrust impacts the OA disease process.

Some limitations require consideration. A formal sample size was not conducted since data were part of an ongoing study and results should be confirmed in a larger sample. This is especially important since few participants had high varus thrust values (Fig. 2). Other factors may contribute to muscular co-contraction (e.g. knee adduction moment), but were not considered due to sample size limitations, and the focus of this study on specific disease characteristics (e.g. history of ACL injury). There

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was heterogeneity within the sample including both men and women, participants with varus and valgus alignment, participants with mild to severe knee OA, and participants with varying levels of pain severity (Table 1). This was done to increase the variability in the measures and make the findings more generalizable; however, additional work should examine how these factors impact varus thrust. Finally, varus thrust is often measured with a therapist making a dichotomous judgement of whether it exists or not. An objective measure of varus thrust was used, which was consistent with previous studies (Kuroyanagi et al., 2012; Mahmoudian et al., 2016). This makes it difficult to compare our results with those of studies that used a clinical judgement of varus thrust (Chang et al., 2010).

In conclusion, vastus lateralis-lateral hamstring and vastus medialis-medial hamstring co-contraction was found to be related to varus thrust. Further study is needed to determine if this co-contraction represents an attempt to stabilize the joint, or is the result of a reflex phenomenon. The impact of varus thrust and muscular co-contraction on disease progression should be further considered.

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Table 1

Means (standard deviation) for demographic and study variables. Frequency is provided for KL score.

Parameter		All participants (n=42, 23 women)	OA-only group (n=23, 15 women)	OA-ACL group (n=19, 8 women)	*P* value*
Age (years)		58 (8)	60 (7)	56 (9)	0.163
Height (m)		1.68 (0.11)	1.65 (0.11)	1.70 (0.10)	0.153
Body mass (kg)		78.99 (16.91)	80.19 (17.22)	77.55 (16.88)	0.621
BMI (kg/m^2)		28.17 (5.98)	29.58 (7.23)	26.46 (3.44)	0.092
MAA (^{o})†		-1.49 (5.55)	-0.75 (6.24)	-2.35 (4.66)	0.366
ICOAP (/100)		23 (20)	23 (21)	23 (19)	0.947
Gait speed (m/s)		1.23 (0.15)	1.22 (0.14)	1.25 (0.15)	0.515
Varus thrust (^{o})		2.99 (2.33)	3.15 (2.50)	2.79 (2.16)	0.630
Co-contraction ratio	VL-LG	10.28 (9.47)	11.25 (11.50)	9.10 (6.32)	0.471
	VL-LH	21.26 (17.91)	23.89 (22.09)	17.90 (10.09)	0.294
	VM-MG	8.69 (7.81)	8.68 (8.25)	8.70 (7.46)	0.993
	VM-MH	18.07 (13.16)	19.00 (15.35)	16.99 (10.39)	0.631
KL scores† (frequency)	1	3	2	1	0.263
	2	18	7	11	
	3	14	9	5	
	4	6	4	2	

Abbreviations: OA (osteoarthritis), VL (vastus lateralis), VM (vastus medialis), LH (lateral hamstring), MH (medial hamstring), LG (lateral gastrocnemius), MG (medial

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gastrocnemius), KL (Kellgren-Lawrence) scores, BMI (body mass index), MAA (mechanical axis angle), and ICOAP (Intermittent and Constant Osteoarthritis Pain).
*_P_ values were from the unpaired t-tests (parametric) or Mann-Whitney tests (non-parametric) that compare OA groups.
[†]One participant was missing MAA and KL scores.

Table 2

Results from the regression analyses.

Muscle Pairs (sample size)	Predictors	B	95% Confidence interval		*P* value*	R^2 change
			Low	High		
Vastus Lateralis-Lateral Hamstring (n=40)	KL score	-0.199	-1.024	0.626	0.628	0.025
	Group	0.233	-1.065	1.531	0.718	<0.001
	VL-LH CCR	0.081	0.042	0.119	**<0.001**	0.327
Vastus Lateralis-Lateral Gastrocnemius (n=41)	KL score	0.278	-0.704	1.260	0.569	0.023
	Group	-0.117	-1.648	1.413	0.877	0.001
	VL-LG CCR	0.031	-0.054	0.117	0.462	0.014
Vastus Medialis-Medial Hamstring (n=40)	KL score	0.298	-0.620	1.217	0.514	0.043
	Group	-0.209	-1.639	1.221	0.769	0.003
	VM-MH CCR	0.063	0.007	0.119	**0.028**	0.121
Vastus Medialis-Medial Gastrocnemius (n=39)	KL score	0.601	-0.418	1.620	0.239	0.076
	Group	-0.098	-1.611	1.416	0.897	<0.001
	VM-MG CCR	0.062	-0.038	0.163	0.218	0.040

Abbreviations: CCR (co-contraction ratio), VL (vastus lateralis), VM (vastus medialis), LH (lateral hamstring), MH (medial hamstring), LG (lateral gastrocnemius), MG (medial gastrocnemius), b (unstandardized coefficient), and KL (Kellgren-Lawrence).
*_P_ values were for the t-statistics for the unstandardized coefficients (b). Significant _P_ values are bolded.

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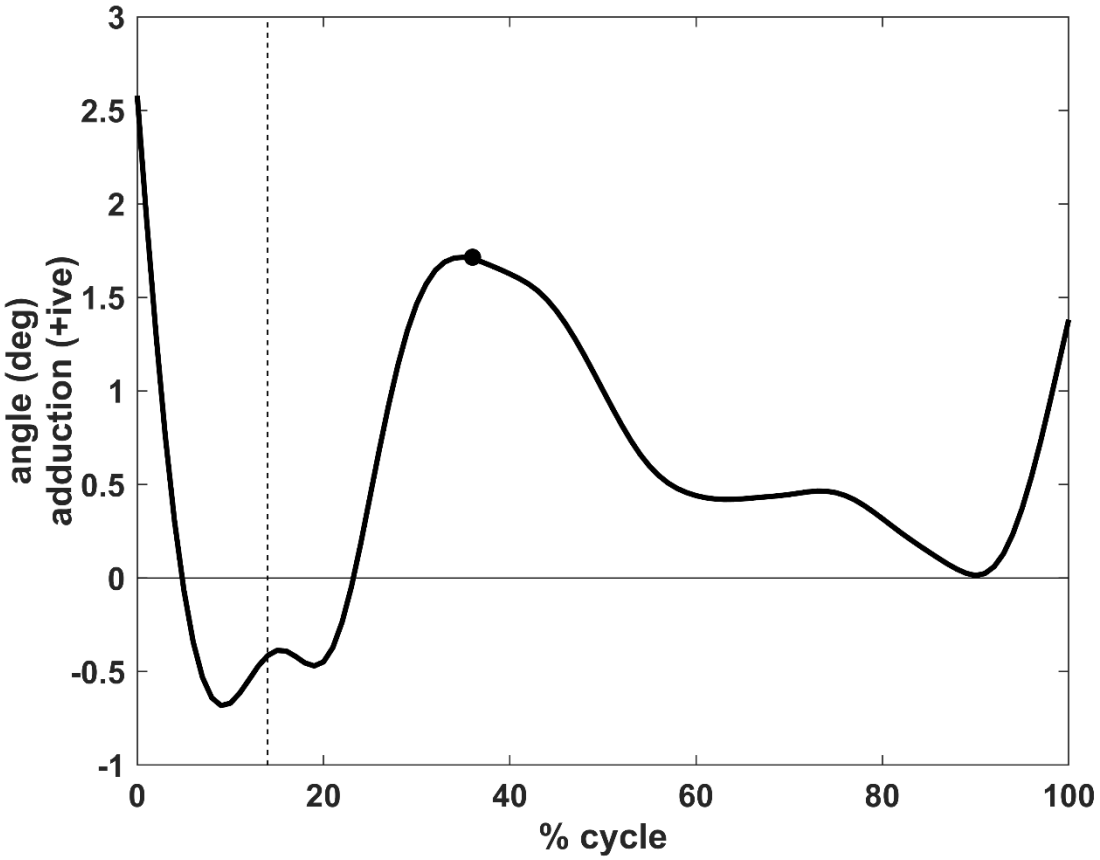

Fig. 1: Sample mean (black line) of knee adduction angle from 100ms prior to heel strike to toe off (normalized to 100%) for all participants. Dashed vertical line and circular marker show approximate timing of heel strike and maximum adduction angle during stance, respectively.

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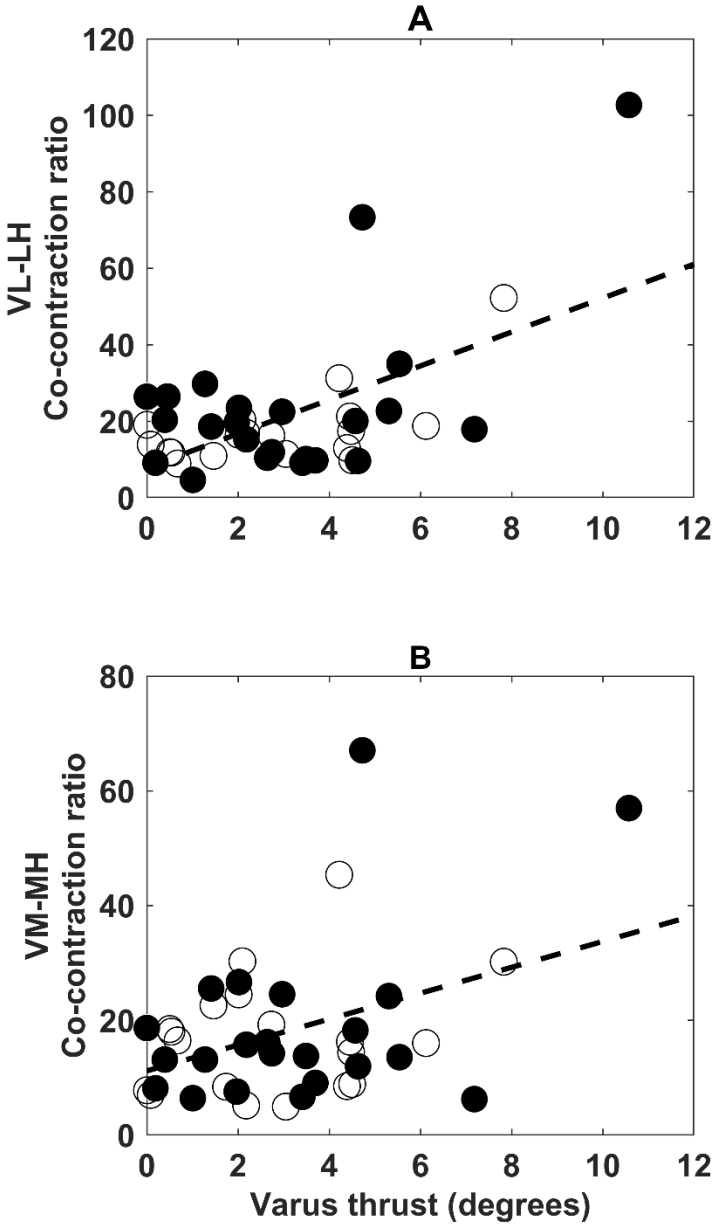

Fig. 2 Scatter plots and lines of best fit showing the association between varus thrust with (a) vastus lateralis–lateral hamstring (VL-LH; r=0.588) and (b) vastus medialis–medial hamstring (VM-MH; r=0.393) co-contraction ratios in participants with knee osteoarthritis (OA). Individual data for participants from OA-only (black, filled dots) and OA-ACL (open dots) groups are shown. Lines of best fit are for the combined groups and are not adjusted for severity and OA group control variables.

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