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What predicts the first peak of the knee adduction moment?

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Abstract

Introduction—The first peak of the knee adduction moment curve during walking has been shown to be a good clinical surrogate measure of medial tibiofemoral joint loading and osteoarthritis. Defining the relative contributions of the variables that dictate the knee adduction moment, such as center of mass, center of pressure, vertical ground reaction force, and knee adduction angle (i.e. lower limb alignment), has not been formally investigated within the same cohort of individuals.

Purpose—Therefore, the goal of this study was to determine which of these variables is the biggest determinant of the first peak of knee adduction moment curve.

Methods—Instrumented gait analysis was collected for 30 individuals. Variables significantly correlated with the peak knee adduction moment were input into a stepwise multi-variable linear regression model.

Results—The knee adduction angle predicted 58% of the variance in the first peak knee adduction moment and the vertical ground reaction force magnitude predicted the second most variance (20%).

Conclusions—The most effective way to modify the peak knee adduction moment may be to change the knee adduction angle (e.g. offloader brace), followed by changing the vertical magnitude of the ground reaction force (e.g. cane use).

Introduction

Medial tibiofemoral osteoarthritis (OA) is a multifactorial problem of which abnormal loading of the medial aspect of the joint is regarded as an important contributing factor [1, 2]. Since direct measurements of tibiofemoral contact stress are difficult to measure *in vivo*, the external knee adduction moment (KAM) has been shown to be a good clinical surrogate measure of medial tibiofemoral joint loading [3]. The peak knee adduction moment has been

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shown to predict the severity of OA [4] and presence of symptoms [5]. Also, patients with medial compartment OA tend to have a higher first peak KAM [6]. This has led to plethora of treatment options that attempt to lower the peak KAM.

Numerous potential gait modifications have been proposed to reduce the KAM. These alterations include decreased walking speed, increased stance width, toe-out, medial thrust gait, trunk sway, high mobility shoes, variable stiffness shoes, wedge insoles, offloader braces, and canes [7]. These interventions aim to alter four variables associated with the KAM: ab-adduction of the knee, magnitude of the ground reaction force (GRF), the location of the body's center of mass (COM), and the location of the center of pressure (COP). However, the contribution of each of these four variables to the KAM remains largely unknown. Identification of which variable(s) most closely predict the KAM would then help clinicians develop more specific and efficacious interventions.

There have been a few investigations into the factors associated with the knee adduction moment. For example, Hunt et al. examined the correlation of the KAM to the frontal plane moment arm and the magnitude of frontal plane GRF in patients with OA. They found the magnitude of the knee adduction moment to be most associated with the magnitude of the moment arm ($r = 0.57$), which was inferred to be more dependent on knee adduction, followed by the magnitude of the frontal plane GRF ($r = 0.25$) [8]. In a follow up study, Hunt et al. examined the correlation between knee adduction moment and knee adduction, WOMAC pain score, gait speed, toe-out angle, and lateral trunk lean in patients with OA. They concluded that knee ab-adduction ($r = 0.51$ and $r = 0.61$), followed by trunk lean ($r = -0.39$ and $r = -0.33$), most correlated with the first and second knee adduction moment peaks [9]. While these studies have addressed two factors, dynamic knee adduction and COM translation as measured by the trunk angle, they have not considered other variables that have been modified to alter the KAM. In addition, while studies have reported on the effect specific gait modification strategies have on the KAM (e.g. lateral wedge insoles[10]), the contribution of each factor cannot be elucidated since each strategy may have altered more than one variable at a time. Also, previous reports have used symptomatic patient populations which makes it difficult to assess how much of the observed mechanics are related to altering the KAM versus a reaction to pain. Indeed, pain has been correlated with the KAM[11]. While the current literature is informative as to the potential individual contributions of these modifiable factors to peak KAM, a study considering all four possible factors in the same cohort of healthy pain free controls is lacking. Identifying these features in a healthy population first would be an important step towards the further development of injury prevention and treatment programs.

Defining how modifiable factors such as COP, COM, ab-adduction knee angle, and GRF magnitude are predictive of the first peak of the KAM is needed to provide clinicians with clearer insights into which variables to manipulate when prescribing a treatment to reduce abnormally high KAM. The literature has found knee adduction, trunk lean, and the magnitude of the GRF to explain 32–37% [8, 9], 11–15% [9], and 6% [8] of the variance in the KAM, respectively. This leaves 42% unaccounted for, which may be due to COP location. Therefore, the goal of this study was to determine which variable is the biggest determinant of the knee adduction moment: the location of the center of pressure, the location of the body's center of mass, knee adduction angle, or the magnitude of the ground reaction force. We hypothesized that the COP location would predict the most amount of the KAM variance, followed by the knee adduction angle, the COM location, and the vertical and medial GRF.

Methods

Data Collection

Following a protocol approved by an institutional review board, subjects were recruited from the local community via word of mouth. After providing informed consent, motion capture data was collected for 30 subjects (mean age:24 SD:3 yrs, mean height: 1.66 SD: 0.05 m, mean mass: 59.6 SD: 7.0 kg) walking on a treadmill (mean self-selected speed of 1.31 SD: 0.11 m/s). Forty-nine retroreflective markers were placed on the subject using a previously established configuration (Figure 1) [12]: anatomic markers on the L4–5 junction, bilateral iliac crests, anterior superior iliac spines, greater trochanters, medial and lateral femoral epicondyles, tibial plateaus, malleoli, and the first and fifth metatarsal heads. Tracking markers were placed on rigid shells on the thighs, shanks, and posterior aspects of the shoes. Three-dimensional marker trajectories were measured during walking by sampling at 200 Hz with a 15 camera motion analysis system (Motion Analysis Corp, Santa Rosa, USA) while simultaneously collecting force data at 1200 Hz using an instrumented Bertec treadmill (Bertec, Columbus, OH).

Knee Kinematics and Kinetics Calculations

Visual 3D (C-motion, Germantown, MD, USA) was used to filter the data, calculate a functional hip joint center [13], perform inverse kinematics, and perform inverse dynamics. Marker data was filtered at 8 Hz and force data filtered at 35 Hz using a fourth-order low-pass zero-lag Butterworth filter. A residual analysis was performed on the data and used to choose these cutoff frequencies (Winter, 2009). Using a previously established biomechanical model [14], joint angles and moments were calculated according to successive body fixed rotations using the order of flexion-extension, ab-adduction, followed by internal-external rotation [15]. The mass properties of the segments were modeled as conical frustums [16]. The knee adduction moment (Figure 2), a result of inverse dynamics, was resolved into the coordinate system of the tibia. Custom Matlab code (MathWorks Inc., Natick, MA) was used to extract the first peak knee adduction moment as well as kinematic variables at the same instant in time as the peak knee adduction moment: the adduction angle of the tibiofemoral joint, the location of the center of pressure relative to the foot origin (centered between the malleoli), the magnitude of the ground reaction force in the vertical and medial-lateral directions, and the global position of the body's center of mass. The body COM did not include the head or arms. Data was collected from 5 trials for each subject and then averaged. Knee adduction moment was normalized to body mass times height [17] and ground reaction force by body weight squared [18]. These variables affect the KAM through either the moment arm of the ground reaction force (knee adduction angle, location of center of pressure, and location of center of mass) or the ground reaction force directly.

Statistical Analysis

Using SPSS (SPSS Inc., Chicago, IL), variables were checked for normality using the Kolmogorov-Smirnov test with a Lilliefors significance correction. Subsequently, Pearson's correlations coefficients were calculated and those variables significantly correlated with the peak knee adduction moment were input into a forward stepwise multi-variable linear regression model (P_{in}=0.05, P_{out}=0.1) to determine the amount of variance in KAM explained by the kinematic variables. Effects due to multicollinearity were limited by ensuring the Pearson's correlation coefficients between variables input in the regression model were less than 0.8 [19]. Model fit to the data was examined using the Durbin-Watson value [19]. The assumption of homogeneity of variance and linearity was verified by qualitative inspection of the regression of standardized residual versus regression of standardized predicted value plot. Since previous work has found trunk lean (i.e. COM location) to be a predictor of KAM [9], the correlations of COP (i.e. GRF location) and GRF magnitude with COM location were also investigated as a secondary analysis to better understand the mechanism behind how COM may affect KAM.

Results

The superior-inferior location of the COP with respect to foot origin ($r = -.450$, $p = 0.013$), vertical magnitude of the GRF ($r = 0.676$, $p < 0.001$), and the knee adduction angle ($r = 0.762$, $p < 0.001$) were significantly correlated with the knee adduction moment (Table 1) and thus input in the multi-variable linear regression model. There was no collinearity found between these variables (Table 1). The knee adduction angle and vertical magnitude of the GRF were significant predictors of the first peak KAM (Table 2), explaining 58% and 20% of the variance, respectively (Figure 3). The Durbin-Watson value of the linear regression model was 1.865. A higher first peak KAM was associated with increased knee adduction angle and vertical magnitude of the GRF. Even though the superior-inferior location of the COP was correlated with the KAM, it was not a significant predictor in the regression model (explained <2% of the variance when forced into the linear regression model, Table 2). There was no correlation found between the knee adduction moment and the medial-lateral location of the COP, the location of the body COM, or the medial-lateral magnitude of the GRF.

The medial-lateral location of the COP was significantly correlated with the medial-lateral location ($r = -0.420$, $p = 0.026$) and superior-inferior location ($r = -0.458$, $p = 0.014$) of the COM. No correlation was found between COM location and the magnitude of the GRF in either the vertical or medial-lateral direction.

Discussion

The knee adduction moment has been used as a surrogate measure of medial tibiofemoral cartilage loading, especially in the development of non-pharmacological treatments in patients with medial compartment tibiofemoral OA. In order to develop non-surgical options to treat these patients and reduce cartilage loading, it is imperative to first define what factors affect the KAM. We investigated the association of the center of mass, center of pressure, adduction angle, and ground reaction force magnitude on the KAM, finding that the adduction angle, followed by the vertical magnitude of the GRF, are the two main predictors of the first peak KAM. This provides information on which strategies might be the most effective in altering KAM.

There was a significant association between knee adduction angle and the peak KAM, with the adduction angle predicting 58% of the variance. These results are in agreement with earlier studies where alignment has been shown to explain 25%–50% of the first peak of the KAM in osteoarthritic individuals [9, 20], a 50% reduction in KAM after a tibial osteotomy [7, 21], and a 19–50% reduction in medial thrust gait [7]. As the knee adduction angle increases, the medial compartment experiences greater compression loads in the cartilage. As this greater compression force in the medial compartment is not acting at the knee joint center, it then adds to the knee adduction moment about the knee joint center. Knee offloader braces have been designed and advocated as a potential mechanism to decrease the KAM by altering knee alignment to be in a more abducted configuration [22–24]. In addition, variable stiffness shoes have also been shown to increase knee abduction angle and decrease the first peak knee adduction moment [25–27]. The results of the current study suggest that using these types of interventions would address the largest determinant of the KAM as opposed to other potential measures and provide additional evidence of the mechanism behind which these interventions are effective.

There was also a significant correlation between the vertical magnitude of the GRF and the peak KAM, which accounted for 20% of the variance in peak KAM. This result suggests that the next effective treatment besides ab-adduction alignment is one that alters the vertical GRF (e.g. canes or walking poles, weight loss). This result is in agreement with a review [7] that cane use may reduce the peak KAM by the second largest amount. Since the KAM is mostly determined by the frontal plane magnitude of the GRF and its moment arm about the knee joint center [8], a direct reduction in GRF would also result in a decreased KAM. When a cane is used, part of the GRF is shifted to the cane and the GRF under the foot reduced, hence the decrease seen in KAM [28].

Trunk sway is thought to alter the COM and line of action of the GRF, thus effectively altering the moment arm of the GRF about the joint center to reduce the KAM [9, 29]. No correlation was found between COM and GRF magnitude in either direction, which contradicts the theory that the direction of the GRF is related to the COM position in the frontal plane [9, 29]. No data have been presented in the literature to suggest the COM and GRF direction are related in the frontal plane. In the sagittal plane, the GRF passes through a point superior to the COM rather than through the COM, due to ankle torque modulation to maintain stability during walking [30, 31]. Future work could investigate if these findings extend to the frontal plane as well. The results of the current study are in disagreement with another recent paper that found trunk sway to explain much of the variance in peak KAM [9]. One potential explanation is that there may be other variables altered by trunk sway that were not assessed in the previous study. Since the trunk COM is moving medial-laterally during trunk sway, not only could the COP move, but the magnitude of the ground reaction force may also change, as was shown by the current study’s findings that the vertical magnitude of the ground reaction force explained much of the variance in KAM. We also found a significant correlation between COM and COP. Winter suggests the COP location varies in response to imbalances in the COM location [32]. This relation of COM and COP comes about via the rotational equations of motion. A shift in the COP will in turn alter the torque of the GRF about the COM. Therefore a shift in COM may occur to maintain the desired motion or equilibrium position.

Our results suggest trunk sway may need further investigation to understand how it functions to reduce KAM. Our results may also provide insight into how other current gait modifications alter KAM. Decreased walking speed has been shown to decrease KAM by 8%, which may be due to changes in the GRF [33]. Since our results show 20% of the KAM to be attributed to the vertical GRF, there may be other factors that interact and change during walking speed to affect KAM. Increased stance width can decrease KAM by up to 9% [7, 34], toe-out by 1% [35], and lateral-wedge insoles by 9% [36], all of which are thought to be a result of alterations in medial-lateral COP. However, our results showed medial-lateral COP to not be significantly related to KAM and superior-inferior COP an insignificant predictor (1% of the variance). Therefore, these modifications may be acting through other mechanisms (i.e. GRF, knee alignment) that could be investigated in future studies. High mobility shoes can decrease KAM by 8% by altering the COP and GRF [27, 37]. Our results suggest that these shoes may not be changing the GRF as its main mechanism but rather the COP. Although our results may be used to gain some insight into the relationship between these gait modification strategies and the KAM, they also cannot fully explain the reductions in KAM, thus highlighting that these modifications are multifactorial in nature.

One important study design factor to consider in the interpretation of our results is the use of healthy subjects. In a prospective study, a higher knee adduction moment in healthy elders has been related to the later development of knee pain [38]. Our results suggest targets to reduce the KAM in healthy, asymptomatic subjects to prevent future problems. Also, individuals with symptomatic, painful osteoarthritis may make alterations in their gait, which would make mechanisms of KAM reduction hard to elucidate without this base knowledge in healthy subjects. Future work is needed to extend the results of this study and assess the strength these relationships in osteoarthritis patients.

There are some limitations to consider in this study. Due to the cross-sectional design, causality could not be explicitly established. Future studies could use biomechanical modeling to prove our suggested mechanisms of how each variable alters peak KAM. The results were able to explain 78% of the variance in the first peak knee adduction moment. Although considerable, this leaves 22% unaccounted for. Variables not considered included the inertial terms and the torque the weight of the lower limb produces about the knee joint center (Figure 2). The linear regression model used was also a limitation. A forward elimination regression model was used since this has been used in other cross-sectional studies in the literature [39, 40]. Although a forward method is more likely to miss a predictor than the backward methods, results from a backward method did not affect the interpretation of our results. Finally, the subjects walked on a treadmill rather than overground. Frontal plane moments have been shown to not vary between treadmill and overground walking [41, 42]. Therefore, we expect our results to be generalizable to overground walking.

This study determined which variables explained a majority of the variance seen in the first peak of the knee adduction moment curve during gait in terms of four modifiable variables: the location of the center of pressure, the location of the body's center of mass, ab-adduction angle of the knee, and the magnitude of the ground reaction force. Our results show that ab-adduction angle explains most of the variance in peak KAM, thus suggesting reductions in it may be an effective treatment. Altered vertical GRF magnitude explained the second most variance, suggesting another important variable in the modification of peak KAM. These results can provide insight into critical variables that affect KAM so we can understand current treatment strategies better and develop new ones.

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Highlights

1. Knee adduction angle predicted 58% of the variance in peak knee adduction moment
2. Vertical ground reaction force magnitude predicted 20% of the variance
3. Offloader braces may be most effective way to modify peak knee adduction moment

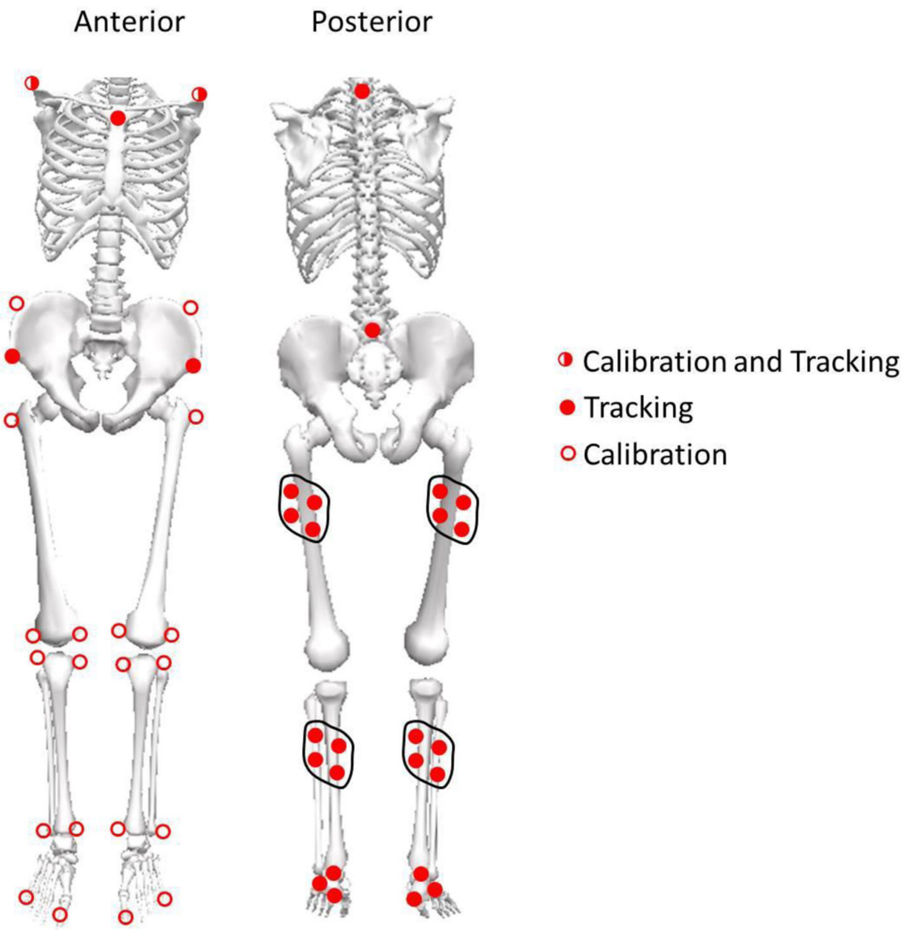
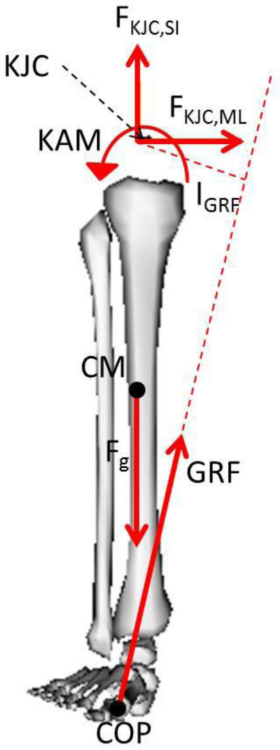


Figure 1.

Forty-nine retroreflective markers were placed on the body: 20 for calibration of the model, 27 for tracking, and 2 for both tracking and calibration.



$$\sum \vec{T}_{KJC} = \vec{I}\vec{\alpha} + \vec{\omega} \text{ x } \vec{I}\vec{\omega} + \vec{r}_{CM/KJC} \text{x } (m * \vec{a}_{CM})$$

$$GRF*l_{GRF} - F_g*l_g + KAM = \text{portion of } (\vec{I}\vec{\alpha} + \vec{\omega} \text{ x } \vec{I}\vec{\omega} + \vec{r}_{CM/KJC} \text{x } (m * \vec{a}_{CM})) \text{ in anterior/posterior direction of shank}$$

$$KAM = \text{inertial terms} - GRF*l_{GRF} + F_g*l_g$$

Figure 2.

Free body diagram of the lower limb with the equation (Newton's equation of motion) used to calculate the knee adduction moment. T_{KJC} = torque about the knee joint center (vector), I = inertia of lower limb (matrix), α = angular acceleration of lower limb (vector), ω = angular velocity of lower limb (vector), $r_{CM/KJC}$ = position vector from center of mass of the lower segment to the knee joint center, m = mass of lower limb (scalar), a_{CM} = acceleration of lower limb (vector), GRF = magnitude of ground reaction force in frontal plane (scalar), l_{GRF} = moment arm of frontal plane GRF (scalar), F_g = weight of lower limb (scalar), l_g = moment arm of weight in frontal plane (scalar), KAM = knee adduction moment (scalar).

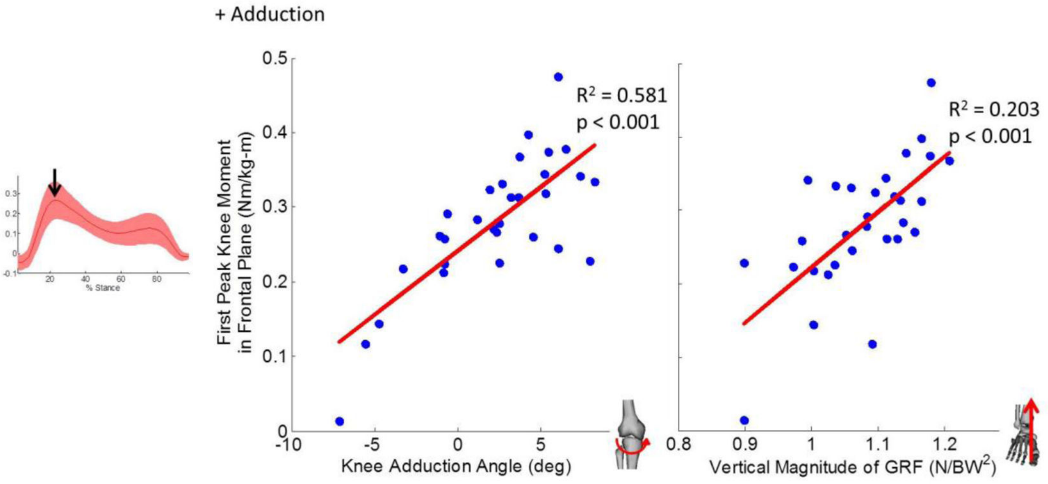


Figure 3.

The knee adduction angle and superior-inferior magnitude of the GRF explained 58% and 20%, respectively, of the variance seen in the KAM.

Table 1

Correlations between variables of interest.

		Peak knee adduction moment	**Medial-lateral location of COP**	**Superior-inferior location of COP**	**Medial-lateral location of body COM**	**Superior-inferior location of body COM**	**Medial-lateral magnitude of GRF**	**Vertical magnitude of GRF**	**Knee adduction angle**
Peak knee adduction moment	Pearson Correlation	1							
	Sig. (2-tailed)								
	N	30							
Medial-lateral location of COP	Pearson Correlation	−.094	1						
	Sig. (2-tailed)	.621							
	N	30	30						
Superior-inferior location of COP	Pearson Correlation	−.450[*]	−.285	1					
	Sig. (2-tailed)	***.013***	.126						
	N	30	30	30					
Medial-lateral location of body COM	Pearson Correlation	.220	−.420[*]	.184	1				
	Sig. (2-tailed)	.261	***.026***	.349					
	N	28	28	28	28				
Superior-inferior location of body COM	Pearson Correlation	−.025	−.458[*]	.087	.359	1			
	Sig. (2-tailed)	.900	***.014***	.659	.061				
	N	28	28	28	28	28			
Medial-lateral magnitude of GRF	Pearson Correlation	.275	.264	−.206	−.311	−.302	1		
	Sig. (2-tailed)	.142	.158	.274	.107	.119			
	N	30	30	30	28	28	30		
Vertical magnitude of GRF	Pearson Correlation	.676[**]	.005	−.179	−.033	−.087	.308	1	
	Sig. (2-tailed)	***.000***	.981	.343	.869	.659	.097		
	N	30	30	30	28	28	30	30	
Knee adduction angle	Pearson Correlation	.762[**]	−.128	−.399[*]	.334	.100	.073	.328	1
	Sig. (2-tailed)	***.000***	.500	***.029***	.082	.614	.700	.076	
	N	30	30	30	28	28	30	30	30

[*] Correlation is significant at the 0.05 level (2-tailed).

[**] Correlation is significant at the 0.01 level (2-tailed).

Table 2

Results of forward stepwise multi-variable linear regression for KAM as the dependent variable

	R	R^2	Adjusted R^2	Change in R^2	p
Knee adduction angle	.762	.581	.566	-	<0.001
Knee adduction angle + vertical GRF	.885	.783	.767	.203	<0.001
Knee adduction angle + vertical GRF + superior- inferior COP	.895	.801	.778	.018	>0.05