Biomechanical difference in forward and lateral lunges and its changes in knee joint moment and functional measurement

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ABSTRACT

Forward lunges (FL) and lateral lunges (LL) are two common variations of lunges, with different knee joint loading. The project aims to investigate the biomechanical differences between three lunges and measure the difference in knee joint moment and its association with Functional Movement Screen (FMS). Fifteen physically active healthy male adults were tested. Subjects were assessed in three movements, namely FMS in-line lunge, FL and LL in randomized order with three trials on each test. Measurements including a) adapted FMS score in 0-3 scale, b) 3D knee joint moment from motion capture system. The normalized knee joint moment in FL is significantly different from LL. There was a moderate and positive correlation shown between FMS score and Knee Flexion/Extension moment. Other correlations showed non-significant results. Knee joint moments were found significantly different between 3 lunges. FMS score cannot directly reflect knee kinetics under current scoring criteria. **Keywords:** Lunges; Functional Movement Screen; Knee; training; Rehabilitation.

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INTRODUCTION

Over the decades, different modes of training on lower limbs have been implemented in a variety of sports to enhance the physical performance, such as speed and muscle strength. These exercises include resistance exercise, interval training, eccentric control training, plyometric training and proprioceptive training. Resistance exercise is well known to increase the muscle mass and isokinetic power of lower limb muscles (Manolopoulos et al., 2013), thus gives an increase on lower limb strength and improving functional performance.

Lunge training is commonly in practice for various kinds of sports, particularly lunge-demanding sports such as fencing and badminton due to its specificity of movement pattern, even before literature investigated its potential effects and implications. A mixed mode of training is the common practice nowadays for coaches to blend different training need into a set of training programme. Football-specific warm-up programme FIFA 11+ showed effectiveness on strengthening lower limb muscles (Impellizzeri et al., 2013) and neuromuscular reaction activity (Takata et al., 2016). Besides, lunge is a functional and important movement, especially on some sports which require this specific motion. Effectiveness of lunge training has been well established on various kinds of sports including badminton, fencing and squash (Cronin et al., 2003; Kuntze et al., 2010). In addition, others have studied the use of lunge training as one of the lower limb rehabilitation exercises in knee condition such as post Anterior Cruciate Ligament (ACL) reconstruction rehabilitation and post meniscectomy rehabilitation (Heijne et al., 2004; Stuart et al., 1996; Thorlund et al., 2012). The multifactorial effectiveness of lunge has been well established in both physical training and rehabilitation.

Forward lunges and lateral lunges (also named as sideway lunges) are two of the most common variations of lunges: Forward Lunge (FL) and (Lateral Lunge (LL). Flanagan reported that the muscle activation and mechanical demand on different muscles between FL and LL is different (Flanagan et al., 2004). Apart from musculature, different knee structures including higher patellofemoral joint stress in lateral lunge and anterior cruciate ligaments also behaved differently in two lunges (Escamilla et al., 2008; Escamilla et al., 2010).

Functional Movement Screen (FMS) is a tool which was developed in 1997, aiming at screening physicals in terms of functional readiness in pre-participation in various sports (Cook et al., 2006). It was designed to reproduce similar kinetics and kinematics of functional movement in both athletes and physical demanding careers, such as fire fighters, and the readiness was reflected from a 4-point scale (Cook et al., 2006). Both upper limb and lower limb functional movement reflected in the seven movements listed in the FMS, giving an individual score from 0-3 and a total score of 0-21. The validity and reliability of FMS was studied in recent systematic reviews and meta-analysis. It is reported that moderate-good to excellent inter-rater reliability in 11 studies reviewed and moderate to good intra-rater reliability in seven studies with ICC range from 0.6 to 0.98 respectively (Beardsley & Contreras, 2014). It is noteworthy that interviewers with less experience versus experienced interviewers give distinguishable results in the reliability of FMS scoring (Gribble et al., 2013).

FMS is also used in prediction of sports-related injuries. For predictive ability, 8 studies investigated the odds ratio on various kinds of lower-limb traumatic injuries (Beardsley & Contreras, 2014). Various subgroups of injuries included ACL rupture (Faude et al., 2006) and hamstring injuries (Brockett et al., 2004). A cut-off score of 14 out of 21 marks was established in various researches (Chorba et al., 2010; Dossa et al., 2014) providing an increase of relative risk and odds ratio below the cut-off scores (Beardsley & Contreras, 2014).

FMS in-line lunge originally designed to examine the participants' rotational and lateral stability during holding a lunge position, giving a stress on hip joint, ankle joint range of motion, as well as knee stability (Cook et al., 2006). The participant required a trunk rotational stability as well as slow control on knee joint during the lunge motion (Cook et al., 2006), thus scoring 3 marks indicated an adequate control of hip, knee and ankle joint. A reduction of score came from movement in torso, inadequate range of movement and unable to maintain the motion in sagittal plane (Cook et al., 2006).

To current knowledge, Whiteside and colleagues (2016) reported the disagreement of the kinetic properties of FMS patterns and the correlation between manual screening score and objective screening score. Nevertheless, the kinematic properties are not measured nor investigated due to the limitation of instrumentation, with no three-dimensional reconstruction of joint reaction forces and loading taken into account. FMS was proven a valid and reliable tool to screen the individual on functional performance, nevertheless studies on individual items was limited. To current knowledge, FL and LL impose a different biomechanical reaction, but FMS in-line lunge have not been thoroughly studied biomechanically. This warrants further cross-sectional investigation on three lunges, putting FMS in-line lunge into comparison. Besides, the correlations between FMS in-line lunge score and biomechanical properties have not been well established.

The primary aims of this study include:

i. To determine differences in normalized knee joint moment in Forward Lunge, Lateral Lunge and FMS In-line Lunge
ii. To identify associations between FMS in-line lunge score in 0-3 point scale and biomechanical properties.

MATERIALS AND METHODS

Study design and sample size calculation

This project was a one group, prospective, cross-sectional study. The sample size was estimated based on the net knee joint moment measurements from Riemann et al. (2013). A power analysis were performed with Type I error of 0.05 (α=0.05) and Type II error of 0.2 (β=0.2), giving a high statistical power of research (1-β) of 0.8 was assumed, and a minimum of fifteen subjects was required for the study.

Table 1. Subject Demographics

	Mean (SD)	Range
Subjects (N)	15	
Age (years)	25 (2.93)	22-33
Weight (kg)	66.7 (8.31)	55-86.9
Height (m)	1.74 (0.09)	1.65-1.85
Dominance (Left/Right)	4/11	

Subjects

Fifteen physically active healthy male subjects volunteered for this study. The inclusion criteria included participants with no resting lower limb pain and physically active with moderate intensity exercise of larger than 150 minutes (2.5 hour) per week as suggested by the American College of Sports Medicine position stand (Garber et al., 2011). Subjects with resting lower limb pain, lower limb surgery <8 weeks, or who were unable to complete the lunge movement were excluded from the study. The demographics of subjects were listed in Table 1. The study was approved by The Joint Chinese University of Hong Kong – New Territories East Cluster Clinical Research Ethics Committee in 2017 (Reference number: 2017.011). Written informed consent was obtained from all subjects.

Lunge variants

All three lunges were labelled as "FL", "LL" and "FMS" throughout the randomization and data processing. For FL, subjects were instructed to maintain forefoot and toes to the front, parallel to the line of stepping, holding both knees at around 90 degree of flexion. For LL, subjects were instructed to maintain forefoot and toes to the front, perpendicular to the line of stepping, holding the knee of dominant leg at around 90 degree of flexion. For FMS in-line lunge, subjects were instructed to maintain a step length around the length of hind limb knee touching the heel of forefoot, maintaining the trunk as straight as possible, without forward/backward bending and lateral bending.

Instrumentation

The marker-based VICON optical system (Motion Analysis, Oxford, UK) with twelve 200 Hz cameras were used to record the lower-extremity kinematics by the 3-D position of markers. Ground reaction force (GRF) were recorded on a 1000Hz force plate (Type 9281B11, Kistler Instrument, Winterthur, Switzerland) with a sampling frequency of 1000Hz and were time-synchronised with motion-analysis data using the Nexus Software (VICON Nexus ver. 1.7.0). Sixteen retro-reflective markers with 1cm diameter were used according to the VICON Plug-In Gait model for lower extremities.

Experimental procedure

Before testing, sixteen retro-reflective markers were placed on the lower limb according to the VICON Plug-in-Gait implementation guideline (VICON Motion System, 2010). Randomization of order of three lunges was performed to reduce the systemic effect of fatigue after each lunging motion. After the randomization of order, the subjects were asked to perform FMS in-line lunge, FL and LL with their dominant leg with subjective comfortable step length according to the order respectively. Standardized demonstration and keynotes of each lunge were given and trials were given for subjects to familiarize each lunge. All three lunges were repeated three trials each with rest of at least 1 minute or longer between each measurement, as per subject requests.

FMS scoring was adopted and all three trials in FMS in-line lunge were scored by two experienced co-investigators. The scoring was ranged from zero to three. The subject was given a score of zero when he felt pain at any body part during the screening. When the subject was not able to follow the movement pattern or could not assume the position to perform the movement, he was given a score of one. Two scores were given when the subject could finish the movement but was required to compensate in some methods to complete the fundamental movement. When the subject conducted the movement correctly and did not have any compensation. All three scores would be given. (Cook et al., 2006). The testing procedures of FMS in-line lunge were video-taped and manual scoring was given on site. Videotape would be reviewed if discrepancies occurred from two scores, and the score would be revised according to the performance in video-tape.

Data processing

The VICON motion analysis system (Motion Analysis, Oxford, UK) with twelve cameras were used to record the lower limb biomechanics. A synchronized piezoelectric force plate was used to measure the centre of support and gravitational reaction force during the lunge process. Plug-in Gait model, which used inverse dynamics using recursive Newton-Euler equations of motion was employed (Davis et al., 1991) to compute knee joint moments (VICON motion system, 2010). Three sets of peak mean values for each lunge and knee flexion angles at each lunge were obtained for further statistical treatment.

Table 2. Descriptive Statistics of Normalized Knee Joint Moment

	Mean (SD) (Nm/kg)	95% CI
FL_Flexion/Extension	15.45 (4.50)	12.96, 17.94
LL_ Flexion/Extension	21.57 (4.83)	18.89, 24.25
FMS_ Flexion/Extension	16.63 (4.30)	14.24, 19.01
FL_Varus/Valgus	5.85 (1.18)	3.33, 8.37
LL_ Varus/Valgus	1.95 (1.94)	-2.22, 6.11
FMS_ Varus/Valgus	4.70 (1.16)	2.22, 7.18
FL_Internal/External Rotation	1.12 (0.34)	0.39, 1.86
LL_ Internal/External Rotation	-0.24 (0.54)	-1.39, 0.90
FMS_ Internal/External Rotation	0.74 (0.40)	-0.12, 1.61

Statistical analyses

The measurements from the dominant leg were used for analyses. The mean values of knee joint moments were normalized by body weight (Moisio et al., 2003). Mean, standard deviation and range was reported (Table 2). The Shapiro-Wilk test was used to determine the normality of the normalized knee joint moments. After the normality of moments were confirmed, an one-way repeated measure Analysis of Variance (ANOVA) was used to examine the significant differences between 3 lunges in Flexion/ Extension moment, Varus/ Valgus moment, and Internal/ External Rotation moment respectively. Effect size was reported in terms of partial eta squared of each ANOVA. Pairwise comparisons were performed using paired t-test if significance were found. Spearman's rank correlation coefficients between FMS score of each FMS in-line lunge and knee joint moments of each FMS in-line lunge were calculated. Linear regression model attempted to obtain a line of best fit using the enter method, and regression equation was reported. The correlation was described according to Zou's suggestion (greater than 0.5 – moderately positive; greater than 0.8 – strongly positive) (Zou et al., 2003). The Intra-class Correlation Coefficient (ICC) values for within-session trials (ICC 2,3) was calculated to evaluate the within-subject variability between trials of each lunge. The ICC classification of Fleiss was adopted to describe the result of ICC values (less than 0.4 - poor; between 0.4 and 0.75 – fair to good; and greater than 0.75 – excellent) (Fleiss, 1986). Association of knee joint moments between 3 lunges was analysed pairwise by Pearson's moment correlation coefficient, and the correlation was described according to Evans' suggestion (between 0.4 and 0.6 – moderately positive; between 0.6 and 0.8 – strong positive; greater than 0.8 – very strongly positive) (Evans, 1996). All data were analysed using SPSS version 23 for Windows (SPSS Inc., Chicago, IL, USA) statistical package. The global significance level was set at $p < 0.05$, and Bonferroni Correction was employed for post-hoc analysis.

RESULTS

Differences of normalized knee joint moments between 3 lunges

For the normalized knee joint moments, mean and SD of three lunges (FL, LL and FMS in-line lunge) was listed in Table 3. All 3-dimensional moment showed significant between-group difference in 1 way repeated measure ANOVA. For Flexion/Extension moment, there was significant difference among three lunges ($F(2,28) = 40.5$, $p < .001$, partial eta-squared = .74). For Varus/ Valgus moment, there was significant difference among three lunges ($F(2,28) = 6.20$, $p = .006$, partial eta-squared = .31). For Internal/ External Rotation moment, there was significant difference among three lunges ($F(2,28) = 6.87$, $p = .004$, partial eta-squared = .33).

Table 3. Differences between FL, LL and FMS in-line lunge (one-way repeated measure ANOVA) with pairwise comparison

	Normalized Knee Joint Moments (Nm/kg)			F	Partial eta squared	p value
	FL	LL	FMS			
Flexion/Extension	15.45	21.57	16.63	40.475	.743	<.001***
Varus/Valgus	5.85	1.95	4.70	6.195	.307	.006**
Internal/ External Rotation	1.12	-0.24	0.74	6.871,	.329	.004**

	Flexion/Extension		Varus/Valgus		Internal/External Rotation	
	LL	FMS	LL	FMS	LL	FMS
FL	t=8.09***	t= -1.78	t=3.12**	t=1.53	t=3.94**	t=1.10
LL		t=6.62***		t= -2.07		t=-2.23
FMS						

*Note: *: p < .05, **: p < .01, ***: p < .001*

Pairwise comparison with multiple paired t-test with Bonferroni correction was performed (Table 3). For Flexion/ Extension moment, there was significant higher normalized Flexion moment of LL compared to FL ($t(14) = 8.09$, $p < .001$) and FMS in-line lunge ($t(14) = 6.62$, $p < .001$). For Varus/ Valgus moment, there was significant lower normalized Varus moment of LL compared to FL ($t(14) = 3.12$, $p = .007$). For Internal/ External Rotation moment, there was significant lower normalized Internal Rotation moment of LL compared to FL ($t(14) = 3.94$, $p = .001$). Other pairwise comparisons were not statistically significant.

Correlation between FMS score to knee joint moments

FMS score obtained in FMS in-line lunge trials were analysed pairwise. The descriptive statistics and frequencies were listed in Table 4. Since no subjects reported pain during all FMS in-line lunge, nil sample of score 0 were obtained. There was a moderate, positive correlation between FMS score and Knee Flexion/Extension moment (r_s (45) = .568, p < .001). Other correlations showed non-significant results. The scattered plots of all three moments were listed in Graph 1-3 respectively.

Table 4. Frequency Table and correlation of FMS score

FMS Score	Frequency	Spearman's Rank Correlation		
0	0		r_s	p
1	9	Flexion/Extension	.568***	< .001
2	27	Varus/ Valgus	.162	.29
3	9	Internal/ External Rotation	.038	.81

*Note: *: p < .05, **: p < .01, ***: p < .001*

ICC values for within-session trials

Reliability test was conducted between three trials of each lunge at all dimensions in Table 5. ICC (2,3) was adopted. A high degree of reliability was found between all measurements. The average measure ICC ranged from .963 to .996 in with $p < .001$ at all lunges and dimensions. This gave an excellent repeatability and consistency of 3 trials within subjects for all lunge testing.

Pairwise correlation of knee joint moments between 3 lunges

We analysed the correlation normalized knee joint moments within subjects by Pearson's moment correlation coefficient in Table 6. All three lunges showed moderate to strong positive correlation with r value ranged from .581 to .833. Amongst three moments, Flexion moment showed very strong positive correlation (r = .805 - .833, all p < .001) pairwise respectively. Internal/ External Rotation moment showed variable but statistically significant results (r = .581 - .770, p ranged from .001 to .023), which gave a moderate to strong positive correlation.

Table 5. ICC of 3 trial in different lunges

	ICC Model (2,3)		
	FL	LL	FMS
Flexion/Extension	.968***	.970***	.952***
Varus/Valgus	.996***	.992***	.993***
Internal/ External Rotation	.945***	.983***	.963***

*Note: *: p < .05, **: p < .01, ***: p < .001*

Table 6. Pearson's Correlation Coefficient Between 3 lunges

	Flexion/Extension		Varus/Valgus		Internal/External Rotation	
	LL	FMS	LL	FMS	LL	FMS
FL	r =.805***	r =.833***	r =.787**	r =.792***	r =.770**	r =.588*
LL		r =.806***		r =.744**		r =.581*
FMS						

*Note: *: p < .05, **: p < .01, ***: p < .001*

Linear regression model for significant rank correlation between FMS score and FMS in-line lunge kinematic properties

From the results in Table 4, only normalized Flexion/ Extension moment was significantly correlated to FMS in-line lunge score. A simple linear regression was calculated to predict normalized Flexion/ Extension moment based on FMS score. A significant regression equation was found (F(1,43) = 21.368, p < .001), with an R^2 of .332 and adjusted R^2 of .316. Participants' predicted normalized Flexion moment is equal to 3.926 (FMS in-line lunge score) + 8.813. Participants' normalized Flexion/Extension moment increased 3.926 for each score increased in FMS in-line lunge manual scoring.

DISCUSSION

In this study, we examined biomechanical properties of different lunges in terms of manual scoring (FMS in-line lunge) and normalized knee joint moment (all three lunges). Knee joint moments were found significantly different between lunges. FMS score cannot directly reflect knee kinetics under current scoring criteria.

Comparison between three lunges

The normalized knee joint moment in FL is significantly different from LL. The results aligned with the similar findings in previous studies (Riemann et al., 2013). However, there are no significant difference in normalized knee joint moments between FL and FMS in-line lunge. This result aligns with our hypothesis that there are little differences biomechanically between them since their direction of action and postures are similar to each other. There are no significant difference in normalized knee joint moments between LL and FMS in-line lunge except the part of Flexion /Extension (Table 3). A trend of mean value of normalized knee joint moments with the order of FL, FMS in-line lunge, and LL, was observed.

Interestingly, LL only bear high Flexion/ Extension moment compared to FL and FMS in-line lunge, but low Varus/ Valgus and Internal/ External rotational moments (Table 3). This deviates with our understanding of directional factors attributing to moment, particularly Varus/ Valgus moment of knee during landing task is known to be a risk factor of injury (Hewett et al., 2005). With an order of FL < FMS in-line lunge < LL in overall normalized knee joint moments, we may propose that FMS in-line lunge sits in the middle of challenge in terms of knee kinetics.

Correlation between FMS score and knee joint moments

The FMS score is positively correlated with the normalized knee Flexion/Extension moment from Table 4. This result echoed the only available study conducted by Whiteside et al.(2016), which use IMU as measurement of knee position. In Whiteside's study, it reported a poor to fair agreement between objective measurements in knee kinematics, with a kappa value of 0.20.

Whiteside et al. (2016) developed a self-established scoring criterion for objective scoring using the data captured by IMU units (Whiteside et al., 2016). The scoring criteria depend on the net relative movement, in terms of absolute value of degrees, detected from the IMU unit. The IMU units itself cannot report the knee joint moments generated solely based on the relative positions by calculations from accelerometers and gyroscopes. The angles generated, however, are interrupted by 2 factors: magnetic interference and acceleration/ deceleration speed (Seel et al., 2014) which affects the possibility of using the data to be used as inverse dynamics calculations. The technical consideration of IMU to measurement of knee joint moments in vivo study and correlations generated from IMU is beyond the scope of discussion since VICON system is adopted in our study, and previous studies also did not report any knee joint moments from using IMU measurements.

The validity of using the captioned scale in Whiteside's study (2016) to evaluate manual scoring versus objective measurement is also questionable. The sensitivity of manual scoring is not evaluated in previous studies, thus setting a fixed degree of movement as a basket of scoring criteria may not completely reflect the validity of manual scoring. Nevertheless, this study provides valuable results as the foundation of our study. Our results partially agree the findings from previous studies in one direction of movement. Since the correlation reported in our study is in 3-dimensional moments, the agreement of results will be similar if a resultant knee joint moment was generated and compared.

Clinical Implication of this study

Although our study cannot reflect significant difference amongst all three lunges, the knee joint moments are highly correlated between them. Upon current practice, lunging has been co-operated in injury prevention programme, for instance FIFA 11+, and post-injury rehabilitation programme (McCurdy et al., 2012). Conventional consideration for training progression including progressive training difficulty and sports specificity (Harley 2008), with reports which showed balancing training volume and sports-specific motions plays a role in improving sports performance in both functional outcomes and physiological adaptation (Gibala et al., 2006).

Nevertheless, in tight training schedule, selection of one type of lunge incorporated into a whole-body training protocol is common practice. Since the knee kinetics are highly correlated between three lunges, ordering FL, FMS in-line lunge and LL from lowest difficulty to highest difficulty in static lunging is a justified progression from the results in this study. It may provide predictive ability of knee joint moment in all three lunges in a single clinical test with repeated trials.

On the other hand, FMS scoring cannot directly reflect the high correlation between three lunges in knee joint moment. The result is expected since the scoring only differentiate a three-dimensional moment into two intervals by score 1 and 2. In Whiteside's definition, it reports a three-dimensional change in angle in its scoring criteria (Whiteside et al., 2016). On top of the observation above, FMS in-line lunge, as an assessment tool, has a potential to evaluate the knee biomechanics of both FL and LL. However, an objective measurement/ manual scoring criterion need to be revised to meet the manual score with knee joint kinetics. It is noteworthy that even if the kinetics can be estimated, it is not valid to correlate the biomechanical measurement in FMS to risk of injury (Bakken et al., 2017). Further investigation of data from this study may provide proof on the validity of the objective measurement criteria defined by Whiteside.

Limitation of the study

The study only included male subjects. Although behaviour of knee joint moments for same motion is similar, gender difference in normalized knee joint moment value has been reported in previous studies (Sigward and Powers, 2006). Therefore, the results from this study could only represent healthy, physically active male adults. A relatively small, homogenous sample size also limits the generalizability of the results to other group of populations, such as patient group or sedentary population.

This study is a one-group cross-sessional study. No causative or follow-up performance investigation was carried out. Besides, since there is no complete linear equation being set, the prediction value of FMS score to other lunge is beyond the answer of this study. It is noteworthy that step length, leg length and knee flexion angle during lunge are factors commonly reported attributable to knee flexion/ extension moments in previous studies (Riemann et al., 2013; Barbieri et al., 2013). The above-mentioned factors were yet to be controlled in our trials. Thus the results have slight deviation with strict-controlled studies.

To conclude, knee joint moments were found significantly different between lunges. Besides, FMS score cannot directly reflect knee joint moments under current scoring criteria, unless revised kinetic objective measurement criteria was established. From the positive correlation of knee joint moment between three lunges, this gives a foundation on the value of further studying the association and objective representation between them. A larger scale study or study with prospective study design to better evaluate FMS in-line lunge is warranted for the result of this study.

DECLARATION OF INTEREST STATEMENT

No potential conflict of interest was reported by the authors.

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