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Short communication

## Using force sensing insoles to predict kinetic knee symmetry during a stop jump

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## ABSTRACT

Knee kinetic asymmetries are present during jump-landings in athletes returning to sport following anterior cruciate ligament (ACL) reconstruction, and are associated with an increased risk for sustaining a second ACL injury. The loadsol<sup>®</sup> is a wireless load sensing insole that can be used in non-laboratory settings. The purpose of this study was to determine if the loadsol<sup>®</sup> could be used to predict knee extension moment and power symmetry during a bilateral stop jump task in healthy recreational athletes. Forty-two uninjured recreational athletes completed seven bilateral stop jumps. During each landing, the loadsol<sup>®</sup> (100 Hz) measured plantar load while 3D ground reaction forces (1920 Hz) and lower extremity kinematics (240 Hz) were collected simultaneously. Peak impact force, loading rate, and impulse were quantified using the loadsol<sup>®</sup> and peak knee extension moment, average knee extension moment, and total knee work was quantified using the laboratory instrumentation. Limb symmetry indices were quantified for each outcome measure. Multivariate backwards regressions were used to determine if loadsol<sup>®</sup> symmetry could predict knee kinetic symmetry. Intraclass correlation coefficients (ICCs) and Bland-Altman plots were used to determine the agreement and error between predicted and actual knee kinetic symmetry. Loadsol<sup>®</sup> impulse and peak impact force symmetry significantly predicted kinetic knee symmetry and explained 42–61% of its variance. There was good agreement (ICCs = 0.742–0.862) between predicted and actual knee kinetic symmetry, and the error in the predicted outcomes range from ±18 to ±43. These results support using the loadsol<sup>®</sup> to screen for kinetic symmetries during landing in athletes following ACL reconstruction.

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## 1. Introduction

Athletes returning to sport following anterior cruciate ligament reconstruction (ACLR) have a 30–35% chance for sustaining a second ACL injury to either the surgical or contralateral limb (Paterno et al., 2014; Webster and Feller, 2016). Asymmetrical limb loading during bilateral landing tasks, where the surgical limb load is decreased and the non-surgical limb load is increased, is extremely common among ACLR patients and is believed to contribute to this heightened risk for second ACL injuries (Butler et al.,

2016; Dai et al., 2014; Paterno et al., 2007; Paterno et al., 2010; Renner et al., 2018; Schmitt et al., 2015). Paterno et al. measured landing mechanics in ACLR patients at the time of return to sport and then prospectively monitored for second ACL injuries, finding that lower knee extension moment symmetry was one risk factor for sustaining a second ACL injury (Paterno et al., 2010). As asymmetrical limb loading during landing does not simply resolve with time during rehabilitation and following return to sport (Paterno et al., 2007; Renner et al., 2018), it is imperative that limb loading symmetry be quantified and improved during post-operative physical therapy. However, validated and clinically-accessible instrumentation to quantify limb loading symmetry is currently lacking.

Computing knee kinetics (e.g. knee extension moment or power) requires 3D motion capture with synchronized tri-axial

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force platforms to collect lower extremity kinematics and kinetics. These technologies are not feasible for use in clinical settings as they are expensive, not portable, and require time and expertise to set up, collect, and process data. Recent work has shown that peak force, loading rate, and impulse symmetry in vertical ground reaction forces measured by force plates can explain 55–77% of the variance in knee extension moment and power symmetry during a bilateral landing task (Dai et al., 2014; Nelson et al., 2018). This suggests that kinetic knee symmetry can be quantified through bilaterally measuring ground-based impact forces, which reduces the need for collecting 3D kinematics and makes it easier to assess landing symmetry in a clinical setting. Using load-sensing insoles could be one tool for measuring impact force bilaterally in a clinical setting. The loadsol<sup>®</sup> (Novel Electronics, St. Paul, MN, USA) is a force measuring insole that is relatively inexpensive and light weight, and has the ability to collect and transmit data wirelessly via Bluetooth to any smartphone or tablet. The loadsol<sup>®</sup> has been recently validated against embedded force plates for measuring peak impact force, loading rate, and impulse and for assessing load symmetry using these measures (Peebles et al., 2018). The loadsol<sup>®</sup> could therefore be useful for assessing limb loading symmetry in clinical settings. The first purpose of the present study was to determine whether load symmetry as measured using the loadsol<sup>®</sup> can predict kinetic knee symmetry quantified using standard 3D motion analysis procedures during a bilateral stop jump task in healthy recreational athletes. The second purpose was to test the agreement and error between predicting knee kinetic symmetry using the loadsol<sup>®</sup> and calculated knee kinetic symmetry using 3D kinematics and kinetics. We hypothesized that loadsol<sup>®</sup> measured load symmetry will be significantly predictive of and have excellent agreement with knee kinetic symmetry.

## 2. Methods

### 2.1. Participants

Forty-two healthy uninjured individuals (21 male/21 female; age  $23.1 \pm 3.5$  years; height  $1.73 \pm 0.09$  m; weight  $69.2 \pm 12.6$  kg) were recruited, signed institutional review board approved consent, and participated in the study. All participants were between the ages of 18 and 30, and were recreationally active for at least 30 min, three times per week. Participants were excluded if they had a history of major lower extremity surgery, had sustained a lower extremity injury in the previous two months, had a preexisting condition that limited participation in physical activities, or were pregnant.

### 2.2. Procedure

All participants were bilaterally fitted with a pair of loadsol<sup>®</sup> sensors (Novel Electronics, St. Paul, MN, USA) and standardized footwear (Air Pegasus; Nike Inc., Beaverton, Oregon). The loadsol<sup>®</sup> insoles were calibrated based on manufacturer guidelines which have been previously described (Peebles et al., 2018). Ground reaction forces were collected at 1920 Hz using two tri-axial embedded force plates (AMTI, Watertown, Massachusetts) and lower extremity kinematics were collected at 240 Hz using a 10-camera motion capture system (Qualisys, Goteborg, Sweden) and a modified Helen-Hayes marker set (Fig. 1) (Dai et al., 2014). Each participant completed seven repetitions of a stop jump, where participants ran straight forward for five steps before taking off on one foot, landing on two separate force plates, and then immediately jumping vertically at maximum effort (Butler et al., 2014; Dai et al., 2014). A rest period of 30 s was provided between repetitions. Restrictions were not placed on arm movement, and no additional instructions were given.

### 2.3. Analysis

Data analysis was performed using MATLAB (Version 9, The Mathworks, Inc, Natick, MA, USA) and Visual 3D (C-Motion, Bethesda, MD, USA). The outcomes quantified using the loadsol<sup>®</sup> sensors were peak impact force, loading rate, and impulse. Peak impact force was calculated as the largest peak in the first 25% of stance phase, loading rate was calculated as the peak impact force divided by the time it took to reach the peak impact force, and impulse was calculated from initial contact to toe off of the first landing (Dai et al., 2014; Peebles et al., 2018). The outcomes calculated using the laboratory kinematic and kinetic data were peak knee extension moment, average knee extension moment, and total knee work. Marker trajectories and ground reaction forces were filtered using a fourth-order Butterworth low-pass filter with a cutoff frequency of 7 and 15 Hz, respectively. Knee extension moment and power were quantified bilaterally during the first landing of the stop jump and time normalized from 0 to 100% ground contact, using a cutoff of 25 N to define initial contact and toe off. Average knee extension moment was quantified throughout the entire stop jump and peak knee extension moment and total knee work were quantified during the landing phase of the stop jump, defined as the time between initial contact and peak knee flexion (Paterno et al., 2010). All outcome measures were normalized to body weight. A limb symmetry index (LSI) was calculated for each outcome as the ratio between the non-dominant



Fig. 1. Participant completing the stop jump task while simultaneous loadsol<sup>®</sup>, force plate, and motion capture data is collected.

and dominant limb. This LSI was chosen as it is widely used across literature, (Barber-Westin and Noyes, 2011; Schmitt et al., 2015), and reflects both amount and directionality of asymmetry (e.g. LSIs < 100 indicate that load was greater on the dominant limb). The LSI was calculated independently for each trial and averaged across trials to obtain one symmetry value for each loadsol<sup>®</sup> and each laboratory outcome measure. To define limb dominance, each participant was asked to lightly kick a soccer ball, and the dominant limb was defined as the kicking limb.

#### 2.4. Statistical analysis

Backwards step-wise multivariate regressions were performed to assess the ability of loadsol<sup>®</sup> symmetry outcomes to predict each laboratory knee kinetic symmetry outcome. A significance of 0.05 and 0.1 was used to enter and remove variables, respectively, and an intercept was included in each regression model. Next, knee kinetic symmetry was predicted using the loadsol<sup>®</sup> symmetry outcomes and resulting regression equations. The agreement between the predicted and actual knee kinetic symmetry outcomes was tested using two-way mixed-model intraclass correlation coefficients (ICC 3,k) run for consistency. ICCs above 0.9 were considered excellent, good between 0.75 and 0.9, moderate between 0.5 and 0.75, and poor below 0.5 (Koo and Li, 2016). The error between the predicted and actual knee kinetic symmetry outcomes was visualized using Bland-Altman plots and formally quantified using 95% Limits of Agreement (LoA) analysis (Giavarina, 2015). Significance was set at 0.05 and all statistical analysis was performed using SPSS (Version 24, SPSS Inc., Chicago, IL).

### 3. Results

Descriptive statistics for each knee kinetic symmetry and each loadsol<sup>®</sup> symmetry outcome can be found in Table 1. Only one variable was retained in each regression model (Table 2). Impulse symmetry predicted peak and average knee extension moment symmetry and explained 60.9% and 46.8% of the variance, respectively (both  $p < 0.001$ ). Peak Impact force symmetry predicted total knee work symmetry and explained 41.9% of the variance ( $p < 0.001$ ). Scatterplots, ICCs, Bland-Altman plots, and 95% LoA between the actual knee kinetic symmetry outcomes and predicted knee kinetic symmetry outcomes can be found in Fig. 2.

**Table 1**

Descriptive statistics for each laboratory knee kinetic symmetry outcome and for each loadsol<sup>®</sup> outcome.

	Average	SD	Range
Peak KEM LSI	100.35	14.88	65.98–137.71
Average KEM LSI	100.63	13.57	74.43–54.67
Total Knee Work LSI	108.57	28.99	54.67–169.64
Impulse LSI	103.34	18.41	76.81–157.76
Impact peak LSI	106.57	29.64	57.77–165.60
Loading Rate LSI	109.97	33.64	53.29–204.43

Note: KEM – knee extension moment; LSI – limb symmetry index; SD – standard deviation.

**Table 2**

Multivariate backwards regression results with loadsol<sup>®</sup> symmetry outcomes as independent variables to predict laboratory symmetry outcomes.

	Predictor	Unstandardized regression coefficients	Constant	R <sup>2</sup>	P value
Peak KEM LSI	Impulse LSI	0.630	35.213	0.609	$p < 0.001$
Average KEM LSI	Impulse LSI	0.504	48.520	0.468	$p < 0.001$
Knee work LSI	Peak Impact Force LSI	0.633	41.116	0.419	$p < 0.001$

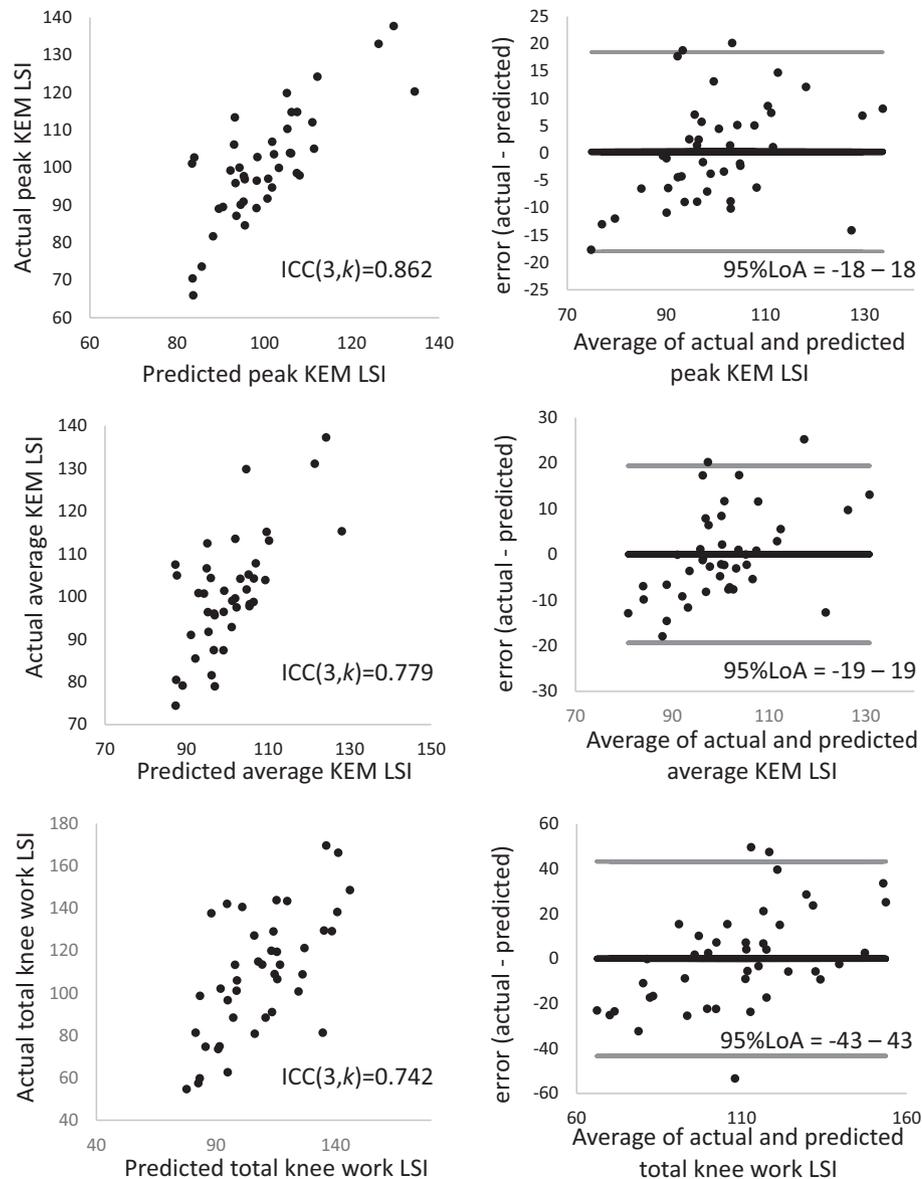
Note: KEM – knee extension moment; LSI – limb symmetry index.

### 4. Discussion

The primary finding of the present study is the loadsol<sup>®</sup>, a wireless and inexpensive load sensing shoe insole, can predict knee kinetic symmetry during landing and explain 42–61% of its variance. These results agree with previous literature which predicted knee kinetic symmetry using force plate measured vertical ground reaction force (Dai et al., 2014; Nelson et al., 2018). Dai et al. found that impulse symmetry can explain 54% of the variance in peak knee extension moment symmetry during a stop jump in 23 ACLR patients (Dai et al., 2014). Nelson et al. found that peak impact force symmetry can explain 66% of the variance in peak knee extension moment symmetry during a drop vertical jump in 21 healthy controls (Nelson et al., 2018). The present study found impulse symmetry can explain 61% of the variance in peak knee extension moment symmetry, which is comparable to these previous studies, though slightly lower. The decrease in variance explained could be partially due to the low sampling rate of the loadsol (100 Hz) when compared with the embedded force plates, which sampled above 1000 Hz in both previous studies (Dai et al., 2014; Nelson et al., 2018). However, the loadsol<sup>®</sup> is relatively inexpensive, wireless, and is not constrained to a single landing location which may improve the ecological validity of testing.

Expanding on previous work, the present study demonstrated that there is good agreement (ICCs = 0.742–0.862) between measured knee kinetic symmetry and predicted knee kinetic symmetry and that the error in the predicted LSI outcomes range from  $\pm 18$  to  $\pm 43$ . These results demonstrate that, for example, differences in predicted peak knee extension moment LSI which are greater than 18 can be confidently attributed to actual differences in knee extension moment symmetry. While this is a relatively large range, ACLR patients typically have peak knee extension moment LSIs below 75% (Dai et al., 2014; Paterno et al., 2007) whereas LSIs for our sample averaged to 100%. The loadsol measures normal force applied to the plantar surface of the foot, which is much different than knee extension moment that requires 3D ground reaction force, 3D center of pressure, and 3D joint kinematic data. We therefore don't expect there to be a perfect agreement between the loadsol and knee kinetic outcomes. However, the loadsol does provide valuable information that is related to laboratory based knee kinetic outcomes. As knee extension moment symmetry is predictive of second ACL injuries (Paterno et al., 2010), future work could explore using loadsol<sup>®</sup> based kinetic symmetry outcomes to assist with predicting and preventing second ACL injuries in an outpatient rehabilitation setting.

The first limitation of the present study is the low sampling frequency of the loadsol<sup>®</sup> (100 Hz). A new generation of the loadsol<sup>®</sup> has recently been released which samples at 200 Hz and is more accurate than the 100 Hz insoles (Peebles et al., 2018). Therefore, using the 200 Hz insoles could improve the relationship between loadsol<sup>®</sup> symmetry outcomes and actual kinetic knee symmetry. However, based on the agreement observed in the present study the 100 Hz insoles are sufficient for quantifying knee kinetic symmetry. Second, while we intend to use the loadsol<sup>®</sup> with ACLR patients, the present study included only healthy participants. As ACLR patients are expected to have more asymmetric knee kinetic



**Fig. 2.** Scatterplots showing the relationship between the actual and predicted knee kinetic symmetry outcomes and Bland-Altman plots showing the error in the predicted symmetry outcomes. Note: LSI – limb symmetry index; ICC – Intraclass correlation coefficient; LoA – limits of agreement; KEM – knee extension moment.

symmetry which could be lower than our regression constants, regression equations developed using patient data are needed to predict knee kinetic symmetry in a patient population. However, the amount of asymmetry present in the current study (LSI range: 68–138%) is comparable with previous literature with ACLR patients (LSI range: 31–112%) (Dai et al., 2014).

In conclusion, limb loading symmetry measured with the loadsol<sup>®</sup> has good-to-moderate agreement with knee kinetic symmetry, and may be an acceptable method to screen for injury risk in a clinical setting.

#### Declaration of Competing Interest

The authors confirm there are no personal or financial conflicts of interest which could have influenced the present manuscript.

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