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Short communication

Construct validation of lower limb segmental excursion as a measure of potential risk for lower limb injury in Division I women's basketball players

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ABSTRACT

The region of limb stability (ROLS) is an inertial sensor-based measure of static knee joint stability, defined by thigh and shank movements of the supporting limb during single limb stance. Changes in thigh and shank movements and/or symmetry differences between limbs may predict risk of injury to the less stable limb or the need for rehabilitation. In this study, construct validity of the ROLS metrics was examined in twelve Division I women's basketball players during pre-season in preparation for their exercise training program. The subjects were categorized based on their injury history during the season: (Group 1) No reported injuries throughout the season, (Group 2) lower limb injury that did not result in missing any games, and (Group 3) lower limb injury that resulted in missing both practice and the remainder of their season. Significant differences were found in ROLS metrics at pre-season between Group 3 and other groups in a prospective cohort study ($p < 0.05$). Study findings provided pilot data for supporting ROLS as a measure of postural stability impairment and potential risk for lower limb injury in athletes.

1. Introduction

A potential risk factor for lower limb injuries is diminished proprioception, which accounts for quality of available proprioceptive information and ability (Han et al., 2015, 2016; Ribeiro and Oliveira, 2007; Riva et al., 2016). Diminished proprioception of the lower limb has been found to create varying degrees of instability due to the lack of afferent sensory input from mechanoreceptors to the central nervous system (CNS) (Jensen et al., 2002; Reider et al., 2003). Altered proprioceptive function significantly challenges the sensorimotor system, especially during static balance maneuvers (Parus et al., 2015). Altered proprioceptive function has been investigated clinically through the resultant amount of body sway during balance testing. For example, it is known that greater amounts of body sway correlate to poorer performance on tasks such as static balance tasks (Doherty et al., 2014; Parus et al., 2015). However, due to compensatory or protective mechanisms above and below the injured joint, some athletes have the capacity to mask the proprioceptive impairment (Brolinson and Gray, 2001; Parus et al., 2015; Zhang et al., 2003). Thus, measuring gross body sway during SLS may be inappropriate to screen athletes with the proprioceptive impairment (Clark et al., 2017; Kim et al., 2018; O'Connell et al., 1998). The unscreened athletes or athletes who unconsciously mask their proprioceptive performance may be at risk for a re-injury (Dallinga et al., 2012).

Recently, we introduced a novel method for quantifying bi-directional segmental excursion of the lower limb during the single limb stance (SLS) test with our inertial sensor-based motion capture system (called CaneSense™) and explored its clinical meaning in athletes with postural instability following sports-related lower limb and head injuries (Kim et al., 2018; Feigenbaum et al., in press). Specifically, two clinically friendly measures were introduced: Region of Limb Stability (ROLS) and ROLS Symmetry Index (SI). We demonstrated that injury to fibrocartilage and

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ligamentous structures of the lower limb results in joint instability that can be sensitively quantified via ROLS and ROLS SI.

Dysfunction in muscles, tendons, skin, and joint structures may lead to impaired postural control of the lower limb ahead of a severe acute injury or re-injury (Ageberg et al., 2005). The purpose of this study was to compare ROLS metrics tested during pre-season within a team of NCAA Division I women's basketball players. The intention of this testing was to use the ROLS metrics to help identify those with impaired postural stability therefore developing a precise exercise program to address their deficits. We hypothesized that the utilization of inertial sensors donned on the lower limb segments in conjunction with the SLS test provides a valuable and valid clinical measure of postural stability impairment in athletes.

2. Methods

2.1. Outcome measures: ROLS and ROLS SI

The ROLS (Kim et al., 2018; Feigenbaum et al., in press) is a novel metric created to quantify the stability of the supporting lower limb by measuring bi-directional excursion via inertial sensors during the SLS test (Fig. 1(a)). As shown in Fig. 1(b), maximum thigh and shank segment excursions in the anterior-posterior (AP) and medial-lateral (ML) planes were used to illustrate the ROLS excursion diagram, a blue line border in Fig. 1(b), and the area of the ROLS excursion diagram is the ROLS value (in cm^2). The ROLS SI (in %) is a single metric generated to quantify differences within individuals by comparing two ROLS values calculated during left and right SLS where 100% suggests absolute symmetry. The ROLS SI is calculated as follows:

$$\text{ROLS SI}(\%) = 100 - \left|100 \times \left(\frac{ROLS_L - ROLS_R}{ROLS_L + ROLS_R}\right)\right| \quad (1)$$

where $ROLS_L$ (cm^2) is the ROLS value measured during left SLS and $ROLS_R$ (cm^2) is the ROLS value measured during right SLS.

2.2. Study subjects

This prospective cohort study protocol reviewed and approved by the University's Institutional Review Board (IRB), included twelve female University of Miami basketball players who signed an approved IRB consent form prior to enrollment.

2.3. Study procedures

Anthropometric and demographic data were collected from all subjects including height, weight, body mass index, position, and year in school (Table 1). Subjects were tested before the season started. Subjects wore standard indoor physical training gear (T-shirt, shorts, socks, and sneakers) with the instrumented knee sleeves (Kim et al., 2018) and performed SLS indoors on a hardwood gymnasium floor.

Prior to administration of the SLS, sensors were calibrated and aligned using an iPad Air 2 tablet (Apple, Cupertino) with a customized CaneSense™ mobile app (Kim et al., 2018). After alignment was complete, subjects performed 30-second SLS trial on each lower limb with 60-second rest between trials. All testers also utilized the CaneSense™ mobile app to collect the data. Trials and testing session data was stored automatically within the device and uploaded to a secure server at the University of Miami Center for Computational Science.

Injury occurrence was tracked and recorded by the athletic trainers of the women's basketball teams during the season (Table 2). A history of injury event(s) over than 24 months was not considered in this study. Injury occurrence was used to classify the athletes and stored as de-identified data.

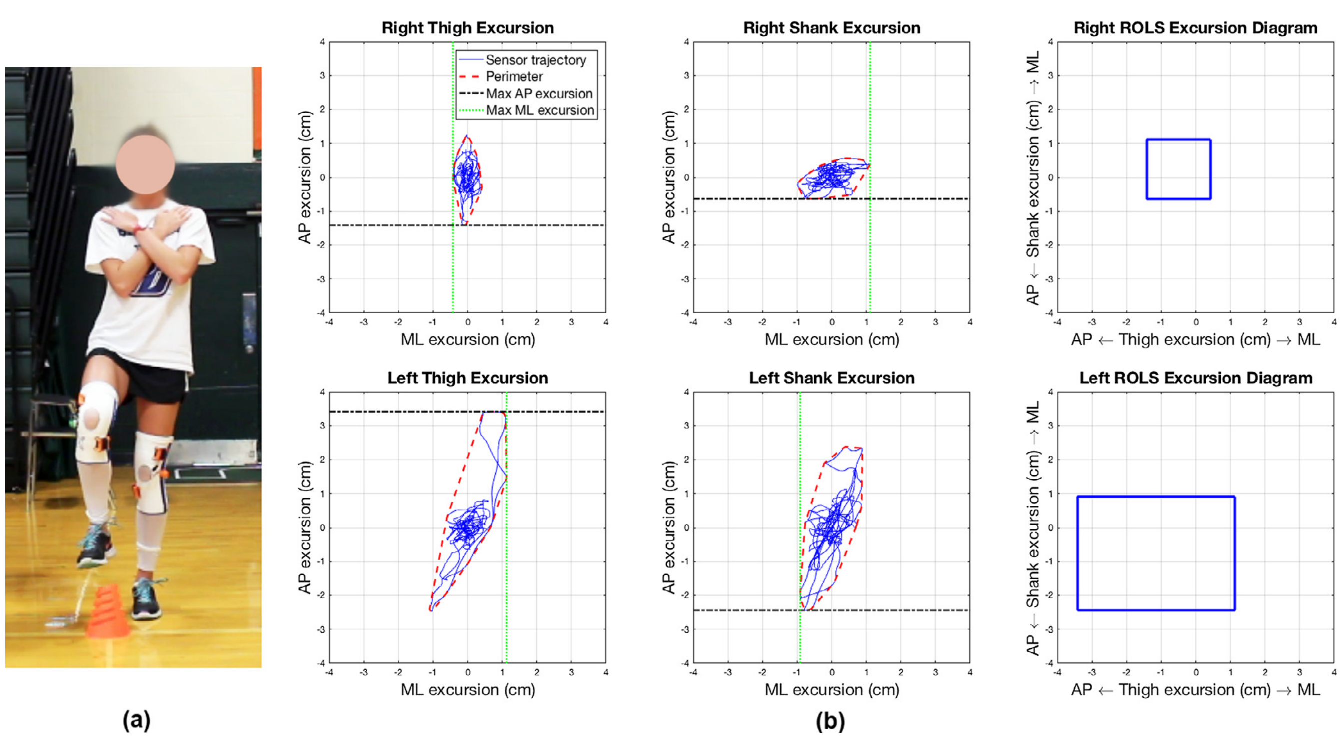

Fig. 1. (a) An example of left SLS testing ($ROLS_L$), (b) An example of the thigh/shank excursion areas and ROLS excursion diagram in a subject during right and left SLS testing. The green dotted line and black dash-dot line are maximum excursions of the thigh and shank in the ML and AP direction, respectively. The red dashed line is a perimeter of each segmental excursion. A blue line border is the ROLS excursion diagram. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Characteristics of Division I women's basketball players based on ROLS performance threshold.

Characteristics	Mean (SD), [Range]			*p*-value
	Green	Yellow	Red	
Height (cm)	175.3 (9.4), [165.1–188.0]	176.5 (3.3), [172.7–180.3]	184.2 (6.4), [175.3–190.5]	0.197
Weight (kg)	70.4 (7.7), [65.3–81.6]	77.7 (15.7), [64.4–100.2]	85.7 (9.2), [74.4–95.7]	0.220
BMI (kg/cm^2)	22.9 (0.8) [22.0–24.0]	24.8 (4.2) [21.0–30.8]	25.3 (2.5) [21.6–27.0]	0.481
Position	Number of subjects			Total ($n = 12$)
	Green	Yellow	Red	
Guard	2	1	2	5
Forward	1	2	1	4
Forward/Center	1	1	1	3
Year	Number of subjects			Total ($n = 12$)
	Green	Yellow	Red	
Freshman	0	2	1	3
Sophomore	2	1	2	5
Junior	2	1	1	4

SD: Standard deviation. Green: ≥80% ROLS SI and ROLS value < 10 cm^2 for both limbs; Yellow: <80% ROLS SI or ROLS value ≥10 cm^2 for one limb; Red: <80% ROLS SI and ROLS value ≥10 cm^2 for at least one limb.

Table 2
Self-reported injury history.

Subject	Category	In-season medical conditions	Past medical history	
			Injury	Time since injury
1	Yellow	(R) Patellar bruise (B) Achilles tendinitis	N/A	N/A
2	Red	(L) Hip impingement	(B) Ankle sprains	During current season
3	Green	N/A	(L) Rotator cuff/labral tear	15 months
4	Green	N/A	(L) Hamstring strain	3 months
5	Yellow	(L) Achilles tendonopathy Bruised tailbone	N/A	N/A
6	Red	(R) Ankle sprain (Grade 1) (B) Patellar tendonopathy	N/A	N/A
7	Red	(L) Proximal tibia/fibula bone bruise	Concussion	9 months
8	Yellow	N/A	(R) Anterior crucial ligament	11 months
9	Green	N/A	(R) Anterior crucial ligament	17 months
10	Green	N/A	(R) Menisectomy	19 months
11	Red	(L) Ankle sprain (Grade 2)	L4-L5 disc herniation	10 months
12	Yellow	(L) Achilles tendonopathy	N/A	N/A

(R): right, (L): left, (B): bilateral.

Table 3
Descriptive statistics (Mean (SD), [Range]) of the ROLS values and ROLS SIs for the three ROLS performance thresholds.

Category	$ROLS_R$ (cm^2)	$ROLS_L$ (cm^2)	ROLS SI (%)
Green	4.6 (1.8), [2.6–6.8]	5.2 (3.1)†, [1.9–9.3]	89.7 (6.3)‡, [84.1–96.6]
Yellow	5.6 (3.7), [2.1–10.6]	4.6 (2.3)†, [2.0–6.9]	67.9 (11.8)‡, [51.2–78.8]
Red	11.4 (9.4), [3.2–25.0]	37.3 (26.0), [19.1–75.9]	67.1 (10.2), [51.1–28.9]

† Difference between Green and Red and between Yellow and Red ($p < 0.05$).
‡ Difference between Green and Yellow ($p < 0.05$), between Yellow and Red ($p < 0.05$), and between Green and Red ($p < 0.05$).

2.4. Statistical analysis and construct validity

Data analysis was performed on IBM SPSS Statistical Software version 22. Three ROLS performance categories, Green, Yellow, and Red, were established to classify single limb balance and postural stability for the athletes: ≥80% ROLS SI and ROLS value < 10 cm^2 for both limbs (Green); <80% ROLS SI or ROLS value ≥10 cm^2 for one limb (Yellow); <80% ROLS SI and ROLS value ≥10 cm^2 for at least one limb (Red). Analysis of Variance (ANOVA), followed by post hoc analysis (Bonferroni testing), was performed to examine differences in the three performance thresholds among the athletes and injury history associated with the performance thresholds.

3. Results

All the athletes completed the SLS test for a maximum of 30 s. Fig. 1 is an example of the thigh/shank excursions and ROLS in a subject during right and left SLS testing. All $ROLS_R$ values, $ROLS_L$ values, and ROLS SIs were included in Table 3. Based on performance categories, Green included subjects 3, 4, 9, and 10; Yellow included subjects 1, 5, 8, and 12; Red included subjects 2, 6, 7, and 11. There were no differences in any anthropometric measures amongst any of the three groups. No subjects classified into Green reported any injuries throughout the course of the competitive season (Group 1). Three out of four of the subjects placed into Yellow, reported a history of left sided lower limb injury during the competitive season, but were rehabbed conservatively and did not result in missing any games (Group 2). All four subjects in Red reported lower limb injuries in a left side that resulted in missing both practice and the remainder of their season (Group 3). Specifically, $ROLS_L$ values, mean (standard deviation (SD)), were 5.2 (3.1), 4.6 (2.3), and 37.3 (26.0) amongst Green, Yellow, and Red, respectively. The ROLS SIs (mean (SD)) amongst Green, Yellow, and Red were 89.7 (6.3), 67.9 (11.8), and 43.8 (10.2), respectively. A $ROLS_L$ value and ROLS SI in Red were significantly different when compared to the other two groups ($p < 0.05$). However, there was no significant difference in $ROLS_R$ values among all groups ($p > 0.05$).

4. Discussion

ROLS criteria found in Table 2 was used to categorize each subject, placing them into groups associated with the presence of postural stability impairments and further risk for injury. Based on the findings presented, it appears there may be a relationship between ROLS values $\geq 10\ cm^2$ or ROLS SI < 80%, and the risk or presence of an underlying injury that affects lower limb stability. Subjects classified as Red are demonstrating postural stability impairments that are consistent with in-season lower limb injuries.

The importance of limb symmetry in both performance capacity as well as injury prevention are well documented in the literature, with symmetry often described as being the second most important injury risk factor behind previous injury history (Chimera and Warren, 2016; Hewett et al., 2013). However, this statement is controversial for some researchers as the contralateral limb function can be also influenced following lower limb injury (Dingenen et al., 2015; Grooms et al., 2015, 2017; Mirkov et al., 2017; Urbach et al., 1999). Though reduced motor afference, particularly from the injured limb, produces a concomitant decrease in neuromuscular activation of the non-injured limb (Nyland et al., 2017). Thus, an injured athlete can display asymmetry in postural stability during SLS due to decreased proprioceptive acuity, pain, or fear of re-injury. Our observations suggest that inertial sensors placed on specific lower limb segments have greater sensitivity to assess the presence of lower limb impairment between and within lower limbs and segments than the force platform (Clark et al., 2017).

Three out of four of the subjects classified into the Red category reported lower limb injuries on the left throughout the course of the season which constituted an accidental coincidence during the study period. For example, Subject 2 was experiencing left hip impingement after having bilateral ankle sprains. The baseline data mirrors her injuries with increased excursion values at the left thigh and increased excursion values at the left and right shank. Subject 7 was experiencing a left proximal tibial-fibular bone bruise. This subject had very high $ROLS_R$ ($32\ cm^2$), with $ROLS_L$ being almost twice as high ($84.1\ cm^2$). Subject 11 was experiencing a left ankle sprain, corresponding with four times greater ROLS area excursion at the left lower limb as shown in Fig. 1. In these three cases, injury to the left lower limb may have resulted in instability and increased excursion areas in the left limb relative to the right. Subject 6 had a right ankle sprain and bilateral patellar tendinitis during the season. Even though she was diagnosed with a Grade 1 right ankle sprain, the reason for missing both practice and the remainder of her season was bilateral patellar tendonitis. Her baseline ROLS values, which were much greater for her left limb ($34.5\ cm^2$) than her right limb ($11\ cm^2$), might be related to more severe impairment at the left knee joint during the season.

The four subjects in the Yellow category may be an area of focus as they are potentially at risk for future injury due to their lower limb stability deficits. Although, this group is not at as high of a risk as the Red category, off-season exercise and training program may be focused on improving the ROLS values and ROLS SI of this group to decrease potential of injury.

There were a few limitations to the study. First, our sample size only consisted of twelve players on a Division I women's basketball team. Even though the groups were evenly distributed, greater sample size and from other schools would allow for the study results to be generalized to a larger population. For example, although significant differences in anthropometrics were not found between the three groups, future work should examine the contribution of body type, training regiments, past injury history and other variables that may have significant effects with a larger population. Second, our methodology consisted of using the application of the inertial sensor during the SLS task only prior to the start of a competitive season. Comparing ROLS values gathered pre-season could shed light on whether a stability deficit at pre-season puts an athlete at risk for lower limb injury. Moreover, ROLS values during the season allow us to monitor changes in postural stability which could allow us to identify the relationship with injury occurrence. ROLS values post-season could allow us to capture altered knee kinematics in relation to in-season workload. Finally, we empirically established three performance categories to classify the performance of single limb balance and postural stability based on our observation and experience in the college-age student athletes. The cut-off ROLS value and ROLS SI for the three performance categories we provided should be examined in a large-scale validation study. Future research should include the application of inertial sensors in pre-season and post-season testing to possibly determine if participating in high-level activity with a lower limb stability deficit, either natural or caused by injury, places an athlete at higher risk of a new or further injury. Additionally, there is a need to determine if there are appropriate interventions with training, bracing or other means to reduce risk of injury once an imbalance in ROLS values are detected.

5. Conclusion

The findings of this study support the hypothesis stated above that the inertial sensors donned on the lower limbs quantify lower limb stability and postural deficits. Study results indicated significant differences in between-limb symmetry and imbalances on the left lower limb of the injured subjects between athletes that were injured and those that were not. Clinicians and coaches can utilize ROLS to be aware that an athlete may be at risk of injury because of increased lower limb segmental excursion or asymmetry.

Conflict of interest statement

No source of funding was received specifically for this study. We have no competing interests to declare.

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