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Original Research

Do neoprene sleeves and prophylactic knee braces affect neuromuscular control and cutting agility?★

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ABSTRACT

Objectives: To evaluate the effects of neoprene sleeves (NSs) and prophylactic knee braces (PKBs) on neuromuscular control and cutting agility.
Design: Markerless motion-capture technology tracked subjects (1) without a brace as a control (2) with NSs and (3) with PKBs during single-leg drop vertical jump (SLDVJ), single-leg squat (SLS), Y-excursion, and cutting movements. Movements were recorded five times per bracing condition in three different sessions.
Setting: University laboratory.
Participants: Ten healthy, active subjects (5 male, 5 female; age range, 22–26 years).
Main outcome measures: Degrees of motion and time to completion.
Results: Use of NSs and PKBs reduced subjects' hip internal rotation in the loading phase of SLDVJ ($p = 0.026$, 0.02) and SLS ($p = 0.005$, <0.001), reduced knee flexion in the loading phase of SLDVJ ($p = 0.038$, <0.001), and reduced knee frontal plane abduction (FPA) with SLS ($p = 0.015$, 0.024) and Y-excursion ($p = 0.002$, 0.005) compared to control. Use of PKBs decreased subjects' hip internal rotation in the Y-excursion ($p = 0.024$) and reduced knee FPA in the SLDVJ loading phase ($p = 0.014$) compared to control. There was no difference in cutting agility for either group ($p = 0.145$, 0.347).
Conclusion: Both NSs and PKBs positively impacted neuromuscular control without impacting cutting agility.

1. Introduction

Knee injuries account for approximately 60% of sports injuries (Rishiraj et al., 2009, 2011). The financial costs associated with these injuries are significant, especially when lost wages and long-term sequelae are considered (Hewett et al., 2005; Britt; Olsen, Myklebust, Engebretsen, & Bahr, 2004; Risberg et al., 2016; Øiestad et al., 2013). In the United States in 2000, the treatment for an anterior cruciate ligament (ACL) tear costs at least $25,000 per injured athlete, leading to a conservative estimate of $2 billion in total costs annually (Rishiraj et al., 2009). More recently, the median total healthcare utilization cost for outpatient arthroscopic treatment of ACL tears has been estimated to be lower, about $13,000 per ACL (Herzog, Marshall, Lund, Pate, & Spang, 2017).

Prophylactic knee braces (PKBs) are non-customized knee braces designed to prevent or reduce the severity of knee injuries (Rishiraj et al., 2009). PKBs became popular in the 1970s when National Football League players began wearing them to protect uninjured knees from medial collateral ligament (MCL) injuries (Rishiraj et al., 2009). PKB manufacturers design and market these braces for injury prevention and/or to reduce knee injury severity while avoiding limitation in performance. However, no conclusive evidence exists concerning their effectiveness (Baltaci et al., 2011; Giotis et al., 2011; Najibi & Albright, 2005; Rishiraj et al., 2009; Rishiraj et al., 2011; Salata, Gibbs, & Sekiya, 2010; Théoret & Lamontagne, 2006). Neoprene sleeves (NSs) are compression

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knee coverings that do not offer any structural support and are intended to increase one's proprioception, or the capacity for one's central nervous system to detect changes in joint kinematics. Thus, NSs are also known as proprioceptive knee braces. Likewise, the effect of NSs and PKBs on performance and fatigue is conflicting. Some studies show no statistically significant positive effects (David L. Greene, Karl R. Hamson, R. Curtis Bay, & Chris D. Bryce, 2000; Liggett, Tandy, & Young, 1995; Rishiraj et al., 2009; Shin, Chaudhari, & Andriacchi, 2011), while others show detrimental effects, including increased rates of knee injuries and an increase in the number of ankle and foot injuries (Beynnon et al., 1997; David L.; Grace et al., 1988; Greene, Hamson, Curtis Bay, & Bryce, 2000; Shin et al., 2011). One crossover randomized controlled trial suggested that neither NSs nor functional knee braces negatively impact performance (Niyousha Mortaza et al., 2012). Furthermore, there has been an increasing number of studies that examine the effects of these braces on neuromuscular control, or the ability to maintain dynamic joint stability (Budini et al., 2018; Hanzlíková et al., 2016; Hanzlíková, Richards, Hébert-Losier, & Smékal, 2019). Poor neuromuscular control can potentially increase the risk for noncontact knee injuries, such as ACL ruptures (Hewett et al., 2005).

Cutting maneuvers involve a rapid change-of-direction while running and are essential for high levels of athletic performance in many sports. However, cutting maneuvers have been associated with noncontact ACL injuries in numerous sports as it may place the knee in valgus and internal rotation, which are known risk factors for ACL injury (Boden, Torg, Knowles, & Hewett, 2009; Cochrane et al., 2010; Havens & Sigward, 2015; Kimura et al., 2010; Krosshaug et al., 2007). Interestingly, sagittal plane movements, such as anterior tibial translation relative to the femur, do not explain noncontact ACL injuries during side-step cutting (McLean, Huang, Su, & van den Bogert, Antonie J, 2004). This further suggests that frontal and transverse plane movements, such as knee abduction and rotation, are primarily responsible for noncontact ACL injuries during cutting maneuvers (Havens & Sigward, 2015).

Therefore, the purpose of this study was to investigate the effects of NSs and PKBs on neuromuscular control and cutting agility during functional movements and simulated cutting maneuvers in a healthy athletic population using a markerless motion-capture analysis system. We hypothesized that neither NSs nor PKBs would have significant effects on neuromuscular control or cutting agility measures when compared to no-brace controls.

2. Materials and methods

2.1. Participants

Ten physically active, healthy recreational athletes (5 males and 5 females, mean ± SD 23.60 ± 1.43 years of age, height 175.77 ± 10.22 cm, mass 72.94 ± 16.70 kg, 23.24 ± 3.44 body mass index) volunteered to participate in the study following institutional review board approval. Recreational athletes were defined as those participating in at least one sport in their leisure time and did not play any sport in a varsity or professional setting. All volunteers provided informed consent and their rights were protected. Subjects were excluded if they had any prior surgery or injury to either lower extremity, or if they had a medical condition that would impair motor or sensory function.

2.2. Functional movement assessment

For each session, subjects completed a set of four movements while being tracked by the Organic Motion BioStage markerless motion capture system [Dynamic Athletic Research Institute (DARI), Overland Park, KS]. The system utilized 14 infrared cameras sampling at 120 Hz, of which 10 were placed above the subject and 4 on the ground in a “capture room” that was laid with retroreflective material (Fig. 1). Body segments were automatically determined by the system during a calibration step, where the subject stood at the center of the room with their arms abducted to 90° until the subject was identified by the system (Fig. 1). The Organic Motion Vision Processor program (DARI, Overland Park, KS) automatically creates a skeleton composed of 21 separate segments, each with 6 degrees of freedom. We examined the segments connecting to the knee, which involved the thigh and shank segments, and the hip, which involved the thigh and sacral spine segments. The sacral spine segment was identified as the lower segment of the spine, which was generated as a straight line from the head and terminating upon intersecting the lines representing the thighs. All movements were performed with the subjects wearing plain black long-sleeve shirt and pants, which were relatively close-fitting but did not inhibit movement in any direction. All subjects wore running shoes of their choice. Markerless motion analysis systems have been validated and used in the literature for motion and gait analysis and joint angle positioning (Corazza et al., 2006; Knippenberg et al., 2017; Perrott, Pizzari, Cook, & McClelland, 2016; Sandau et al., 2014; A.; Schmitz, Ye, Shapiro, Yang, & Noehren, 2013; A.; Schmitz et al., 2015). Furthermore, markerless motion capture has several advantages over marker-based motion capture systems: (1) markers attached to test subjects may hinder subjects' movements, (2) the subject is required to move in a controlled, space-limited space in marker based systems, and (3) markers placed on the skin can move relative to the underlying bones and joints, thereby providing inaccurate joint kinematics.

Subjects completed three sessions wearing:

1. No brace (control),
2. Commercially available NS (Breg Neoprene Knee Support, Breg, Inc., Carlsbad, CA), and

Fig. 1. Organic Motion BioStage (DARI, Overland Park, KS) markerless motion capture system and “capture zone” room. The subject is performing the calibration step, where the subject stands at the center of the room with their arms abducted to 90° until the subject is identified by the system.

3. Custom-fitted PKB (Breg RoadRunner Hinged Knee Brace, Breg, Inc., Carlsbad, CA) fitted by a brace specialist.

Braces were donated by Breg, Inc. (Carlsbad, CA).

2.3. Movement definitions and illustrations

NSs and PKBs were placed on the subject-determined dominant leg for all movements. The dominant leg was identified by asking the subject which leg they would prefer to kick a ball. Neuromuscular control was defined as the unconscious muscular response during movement to maintain dynamic joint stability. Our primary outcome measures for neuromuscular control were the degrees of knee flexion, hip internal rotation, and frontal plane abduction (FPA) and their changes with respect to the use of NSs and PKBs. These outcome measures were chosen because of their relevance to knee dynamic valgus (Hewett et al., 2005). Cutting agility was defined as the speed at which one would be able to rapidly change their direction of movement by 90° throughout 2 gait cycles. Our primary measurement for determining cutting agility was the time to complete the full cutting maneuver. Movements measured included: single leg drop vertical jump (SLDVJ), single leg squat (SLS), Y-excursion, and cutting. The first 3 movements were chosen to measure neuromuscular control as they test the subject's balance, single-leg stability during activity, and have been used in previous studies examining neuromuscular control, especially with regard to dynamics valgus (Hewett, Paterno, & Myer, 2002; Hewett et al., 2005; R. J.; Schmitz, Shultz, & Nguyen, 2009; Shields et al., 2005). We required the participant to complete each movement five times per session, which involved 20 movements total. The order of the movements and sessions were randomized to minimize any learned effect. Sessions were divided by braced condition for a total of 3 sessions divided into 3 separate days to reduce fatigue. Each subject scheduled their 3 sessions on separate days within the same week.

2.3.1. Single leg drop vertical jump

The SLDVJ consisted of jumping down from an 18 inch box onto the dominant foot, followed immediately by a vertical jump using the same foot and landing on that foot. The loading phase of the SLDVJ corresponded to the time from initial contact to the moment of maximum dominant knee flexion (Fig. 2A). A box height of 18 inches was used because it accommodated all subjects.

2.3.2. Single leg squat

The SLS involved the participant standing on the dominant leg, squatting as low as possible without falling or losing center of gravity, and then returning to an upright position (Fig. 2B). Squat depth and velocity were not controlled or standardized across subjects because it was felt that allowing subjects to perform SLS naturally allowed for the most generalizability to the research population of interest.

2.3.3. Y-excursion

The Y-excursion involved the participant weightbearing on their dominant leg and reaching as far as possible with their non-dominant leg in the anterior, posteromedial, and posterolateral directions.(Fig. 2C).

2.3.4. Cutting

The cutting maneuver consisted of a forward sprint, followed by a 90-degree pivot on the dominant foot onto the opposite foot and a continued sprint (Fig. 2D). Overall, the subject was required to rapidly change their direction a total of 90°. Speed of approach was not controlled, as we were interested in using this as a performance metric. The overall time of cutting agility was measured as 2 gait cycles surrounding the time of initial contact during pivot on the dominant foot. Because we did not have a force plate available, gait times were manually determined by video review, which is a relatively reliable method for identifying time of contact and toe-off (Harris & Wertsch, 1994).

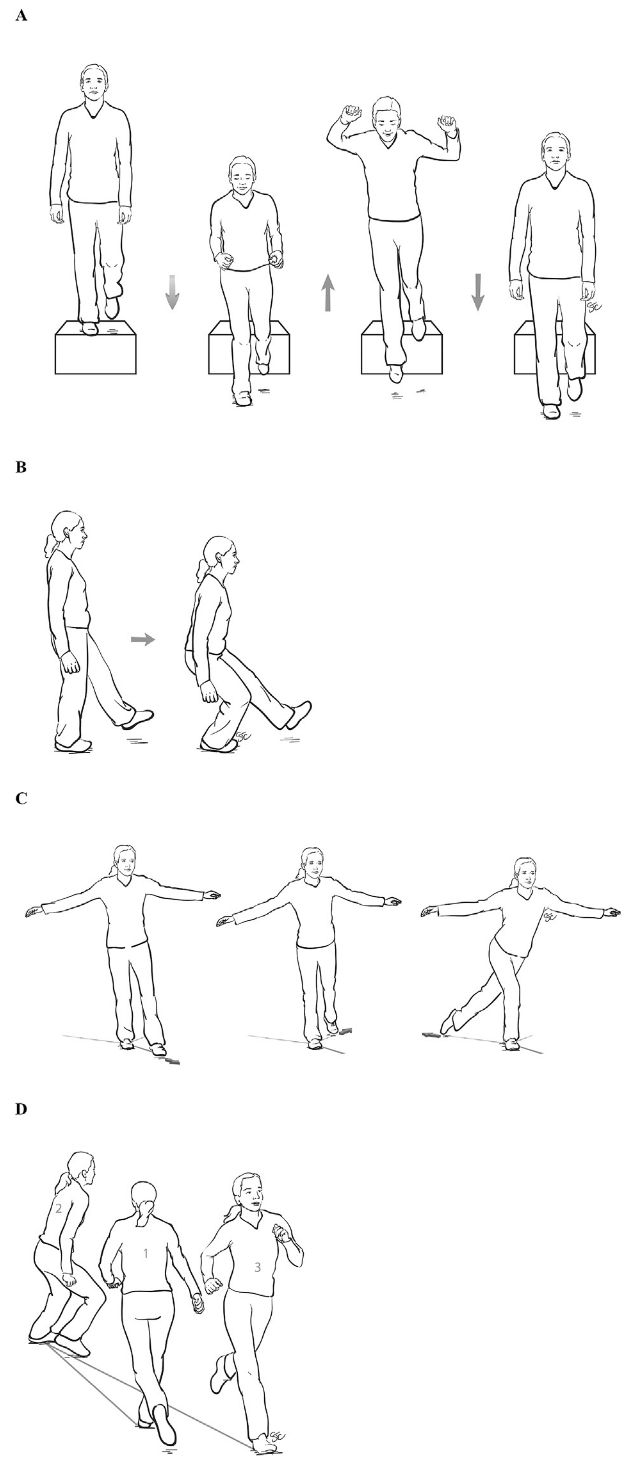

Fig. 2. Movements performed. Fig. 2A illustrates the single leg drop vertical jump (SLDVJ), Fig. 2B: single leg squat (SLS), Fig. 2C: Y-excursion, Fig. 2D: cutting. Illustrations courtesy of Stacy Cheavens, University of Missouri Health Care, Columbia, Missouri, USA.

Measurement values for all movements were obtained at the peak of knee flexion of the dominant leg. For Y-excursion, the time of maximum knee flexion angle of the dominant leg coincided with the time of maximum anterior, posteromedial, or posterolateral reach of the non-dominant, or non-weightbearing, leg. All raw data was automatically filtered and processed by the Organic Motion Vision Processor program. After the body segments were defined, the program automatically produced joint angle measurements, which were then used for analysis.

2.4. Statistical analysis

To account for outliers, box plots with fences were constructed with the intent to exclude and replace values that were extreme outliers (outside of either a lower outer or upper outer fence). Three extreme outliers were found and mild outliers (inside of either a lower outer or upper fence but outside of either a lower inner or upper inner fence) were kept in the dataset. Thus, only 3 outliers were identified out of 600 data points and these outliers were deleted. Assuming an alpha of 0.05, an overall group size in each testing state of 10 patients was determined to be sufficient to detect an effect size of d = 1 (0.89) with 80% statistical power (Wang, Bakhai, Del Buono, & Maffulli, 2013). Percent reduction was calculated based on the difference between the control value and the various braced conditions and that value was divided by the original control value and multiplied by 100. Initially we compared male and female outcomes using a linear mixed model with a random subject effect to account for the repeated measurements of each outcome and fixed treatment and found no significant differences based on sex, thus allowing all participants to be pooled together. A linear mixed model was chosen rather than a repeated measures ANOVA model because it allowed for circumvention of listwise deletion in the event of missing data points. After pooling subjects, each outcome measure was analyzed using a two-sided independent Student's t-test with a significance level of 0.05 using SPSS Statistics 22.0 (IBM Corp., Armonk, NY). It should be noted that a paired *t*-test could not be utilized since 3 data points were deleted after being identified as outliers. This was also done to compare the differences in effects between NSs and PKBs. To test for normality of distribution and homoscedasticity, we used the Shapiro-Wilks test and Levene's test with α-level of 0.05, all of which were not significant. Kurtosis, bounded by $(-2, 2)$, and skewness, bounded by $(-1, 1)$, were also assessed, all of which were within bounds.

3. Results

Overall, motion capture analysis of movements showed significant percent changes with both NSs and PKBs compared to control. These changes were further categorized by movement, as they pertained to neuromuscular control (SLDVJ, SLS and Y-excursion) or cutting agility. Baseline characteristics of movements for the control conditions for male and female participants were similar (Table 1).

Effect of both NSs and PKBs on measured values, during all movements, are compared to the control (unbraced) condition in both Tables 2 and 3, which show raw degree changes and percent reduction, respectively. *P* values represent the comparison of raw values, which are utilized to determine percent reduction. Investigation of the loading phase of single leg drop vertical jump (SLDVJ) showed a significant reduction in knee flexion with both NS ($p = 0.038$) and PKB ($p < 0.001$), compared to control conditions. A concurrent reduction in hip internal rotation during the loading phase also occurred with NS ($p = 0.026$) and PKB ($p = 0.02$). Knee FPA was significantly reduced with PKB ($p = 0.014$), but not with NS ($p = 0.157$), compared to control conditions (Fig. 3).

Table 1
Baseline characteristics in neuromuscular control parameters for male and female participants.

Parameter	Female	Male	*P*-Value
Neuromuscular Control			
SLDVJ, Loading Phase			
Hip Internal Rotation	12.0°±7.8°	12.8°±4.2°	0.520
Knee Flexion	58.9°±6.0°	50.4°±5.4°	0.110
Knee FPA	8.3°±4.0°	6.19°±5.6°	0.900
SLS, Dominant Leg			
Hip Internal Rotation	17.1°±4.5°	16.5°±4.2°	0.740
Knee Flexion	82.2°±6.5°	87.9°±6.7°	0.200
Knee FPA	16.7°±5.1°	16.9°±5.1°	0.630
Y-Excursion			
Hip Internal Rotation	19.5°±2.7°	27.2°±7.2°	0.100
Knee FPA	20.0°±3.8°	20.2°±5.4°	0.390
Cutting Agility			
Time to Completion	0.86s ± .43s	0.75s ± .54s	0.621

SLS: single leg squat, SLDVJ: single leg drop vertical jump, FPA: frontal plane abduction. Values are mean ± SD, all values indicated are in degrees of motion.

For the single leg squat (SLS) with the dominant leg, there was a statistically significant reduction in knee FPA with NS ($p = 0.015$) and PKB ($p = 0.024$), and a reduction in hip internal rotation as compared to control with NS ($p = 0.005$) and PKB ($p < 0.001$). Neither NS nor PKB reduced knee flexion during the SLS movement ($p = 0.136$ and 0.052, respectively) (Fig. 4). During the Y-excursion movement, there was a significant reduction in knee FPA with PKB ($p = 0.005$) and NS ($p = 0.002$). When evaluating hip internal rotation, we noted a reduction in knee FPA with PKB ($p = 0.024$) and with NS ($p = 0.052$), with the latter reduction not statistically significant (Fig. 5).

We observed no statistically significant change in cutting agility between the participant groups. When comparing the effects of NSs and PKBs, we found no significant differences in any of the parameters (Table 2).

4. Discussion

The purpose of this study was to investigate the effects of NSs, which are a form of proprioceptive knee sleeves, and PKBs on neuromuscular control and cutting agility during functional movements and simulated cutting maneuvers in a healthy athletic population using a markerless motion-capture analysis system. Both NSs and PKBs significantly reduced hip internal rotation, knee flexion, and knee FPA compared to no-brace controls. Generally, PKBs reduced these parameters greater than NSs, but these differences were not statistically significant.

To our knowledge, this is the first paper that has used a markerless motion capture system to examine both knee neuromuscular control and cutting agility with respect to the use of NSs and PKBs. Our results of significantly altered joint mechanics with the use of NSs and PKBs are consistent with others who have examined the effects of bracing in both healthy subjects and patients with previous ACL injuries (Giotis et al., 2016; Hangalur et al., 2016; Hanzlíková et al., 2016, 2019; Moon, Kim, Lee, & Panday, 2018). Recently, Moon et al. (2018) found that both the use of knee sleeves and knee braces reduced peak knee flexion angles in subjects performing a double-leg drop and vertical jump (Moon et al., 2018). Although we used a SLDVJ, their findings are consistent with ours that the use of both NSs and PKBs reduced peak knee flexion following a drop and jump. Similarly, Hanzlíková et al. (2016, 2019) found that the use of a proprioceptive brace decreased knee ROM, especially in the transverse plane during a SLDVJ exercise (Hanzlíková et al., 2016, 2019). Interestingly, they also found that

Table 2
Characteristics of neuromuscular control and cutting agility parameters with the use of neoprene sleeves and prophylactic knee braces.

Parameter	Neoprene Sleeve	*P*-Value (compared to control)	Prophylactic Knee Brace	*P*-Value (compared to control)	*P*-Value (comparing braced conditions)
Neuromuscular Control					
SLDVJ, Loading Phase					
Hip Internal Rotation	8.4°±4.4° (−4.0°)	**0.026**	6.2°±4.6° (−8.0°)	**0.020**	0.289
Knee Flexion	46.2°±44.8° (−8.4°)	**0.038**	45.3°±46.8° (−9.9°)	**<0.001**	0.965
Knee FPA	4.5°±2.7° (−2.8°)	0.157	5.8°±3.4° (−4.5°)	**0.014**	0.356
SLS, Dominant Leg					
Hip Internal Rotation	13.4°±12.2° (−3.4°)	**0.005**	12.3°±13.1° (−4.6°)	**<0.001**	0.848
Knee Flexion	82.1°±78.0° (−3.0°)	0.136	81.6°±78.9° (−7.1°)	0.052	0.989
Knee FPA	14.1°±13.2° (−2.7°)	**0.015**	13.7°±13.5° (−3.6°)	**0.024**	0.947
Y-Excursion					
Hip Internal Rotation	17.2°±19.0° (−6.2°)	0.052	18.8°±19.4° (−4.4°)	**0.024**	0.854
Knee FPA	16.5°±17.0° (−3.6°)	**0.002**	16.9°±17.0° (−3.1°)	**0.005**	0.959
Cutting Agility					
Time to Completion	0.70s ± .70s (−0.08s)	0.145	0.80s ± .70s (−0.11s)	0.347	0.753

Values in parentheses are the mean change from control. SLS: single leg squat, SLDVJ: single leg drop vertical jump, FPA: frontal plane abduction. Values are expressed as mean ± SD where appropriate. *P* values represent the comparison of raw values.

Table 3
Percent reduction in neuromuscular control and cutting agility parameters with the use of neoprene sleeves and prophylactic knee braces as compared to control.

Parameter	Neoprene Sleeve	Prophylactic Knee Brace
Neuromuscular Control		
SLDVJ, Loading Phase		
Hip Internal Rotation	32.3% ± 64.6%	50.4% ± 63.3%
Knee Flexion	15.4% ± 18.1%	17.2% ± 14.3%
Knee FPA	38.4% ± 62.8%	19.4% ± 53.2%
SLS, Dominant Leg		
Hip Internal Rotation	20.0% ± 27.3%	26.8% ± 21.9%
Knee Flexion	3.5% ± 8.3%	4.0% ± 7.2%
Knee FPA	16.0% ± 21.2%	18.5% ± 19.7%
Y-Excursion		
Hip Internal Rotation	26.4% ± 18.8%	19.3% ± 16.8%
Knee FPA	17.7% ± 15.2%	15.7% ± 15.4%
Cutting Agility		
Time to Completion	10.0% ± 14.1%	6.1% ± 13.9%

SLS: single leg squat, SLDVJ: single leg drop vertical jump, FPA: frontal plane abduction. Values are expressed as percent reduction compared to control mean ± SD.

the use of the proprioceptive brace increased the peak flexion angular velocities during the SLDVJ, which they hypothesized to be due to increased confidence in performing the exercise (Hanzlíková et al., 2019). Unfortunately, the system we utilized did not provide us with joint angular velocities. Our finding of increased neuromuscular control during exercises demanding increased balance, such as the Y-excursion exercise, with the use of NSs and PKBs is consistent with others (Budini et al., 2018). Budini et al. (2018) found that both the use of proprioceptive bracing and taping decreased angular velocity, which is associated with increased muscular control, in subjects performing an exercise that was almost identical to our Y-excursion exercise (Budini et al., 2018).

Previous studies have shown that increased dynamic valgus – a position during activity in which the knee opens up medially and collapses laterally, moves towards the midline, and experiences internal-external rotation – is a risk factor for ACL rupture (David L. Greene et al., 2000; Hewett et al., 2005; Knowles et al., 2007; Koga et al., 2010; Krosshaug et al., 2007; Olsen et al., 2004; C. Quatman & Hewett, 2009; Carmen Quatman, Quatman-Yates, & Hewett, 2010). Dynamic valgus primarily consists of increased hip internal rotation, knee FPA, and tibial internal rotation. Additionally, it is often accompanied by hyperpronation of the subtalar joint in closed kinetic chain activities (Beckett, Massie, Bowers, & Stoll, 1992; Fischer, Willwacher, Arndt, & Brüggemann, 2018; Powers, 2003; Tiberio, 1987). Dynamic valgus is often incorrectly referred to as "medial collapse" of the knee. However, the term "medial collapse" is not completely inaccurate because excessive subtalar protonation may cause collapse of the medial longitudinal arch of the foot (Beckett et al., 1992; Fischer et al., 2018; Powers, 2003; Tiberio, 1987). Our data demonstrate that subjects fitted with NSs and PKBs demonstrate decreased hip internal rotation and knee FPA during these potentially injury-provoking motions without limiting cutting agility. Recently, Boutris et al. (2018) identified that both a decrease in hip internal rotation and overall limited hip rotation was correlated with an increase in risk for noncontact ACL injury (Boutris et al., 2018). However, their explanation for this correlation was a compensatory increased tibial internal rotation, knee FPA, and anterior tibial translation, which is suggestive of an inadequate neuromuscular control of the knee (Boutris et al., 2018). In our study, we identified a reduction in FPA in conjunction with a decrease in hip internal rotation, which is contrary to what is suggested as the mechanistic link between decreased hip internal rotation and increased risk for noncontact ACL injury. Furthermore, this suggests that our observed reduction in hip internal rotation is a result of improved neuromuscular control of the knee, as our subjects did not compensate for decreased hip internal rotation with increased knee FPA.

Several studies report conflicting results as to whether PKB use increases rates of foot and ankle injuries (Grace et al., 1988; Sforzo, Chen, Gold, & Frye, 1989; Sitler et al., 1990). However, Giotis et al. (2011) showed that PKBs decrease tibial rotation in activities with increased rotational and translational loads, which may further confer decreased rates of noncontact ACL injuries in athletes (Giotis et al., 2011). Other studies have shown that PKBs reduce MCL strain 20%–30%, with conflicting results as to whether ACL strain is reduced; there is bias and a lack of high-level evidence in this literature (Albright et al., 1994; Erickson, Yasuda, Beynnon, Johnson, & Pope, 1993; Rishiraj et al., 2011). Salata et al. (2010) systematically reviewed the incidence of MCL injury with bracing in American Football and did not find a consistent reduction in MCL injuries with the use of bracing (Salata et al., 2010). However, previous studies conducted by West Point and the Big Ten Conference suggest that linemen, linebackers, and tight ends achieved the most benefit from bracing, with a lower incidence of MCL injuries (Albright et al., 1994; Najibi & Albright, 2005).

Some concerns exist that bracing may negatively affect cutting agility, which may potentially affect athletic performance as cutting is integral to performance in many sports. However, we observed

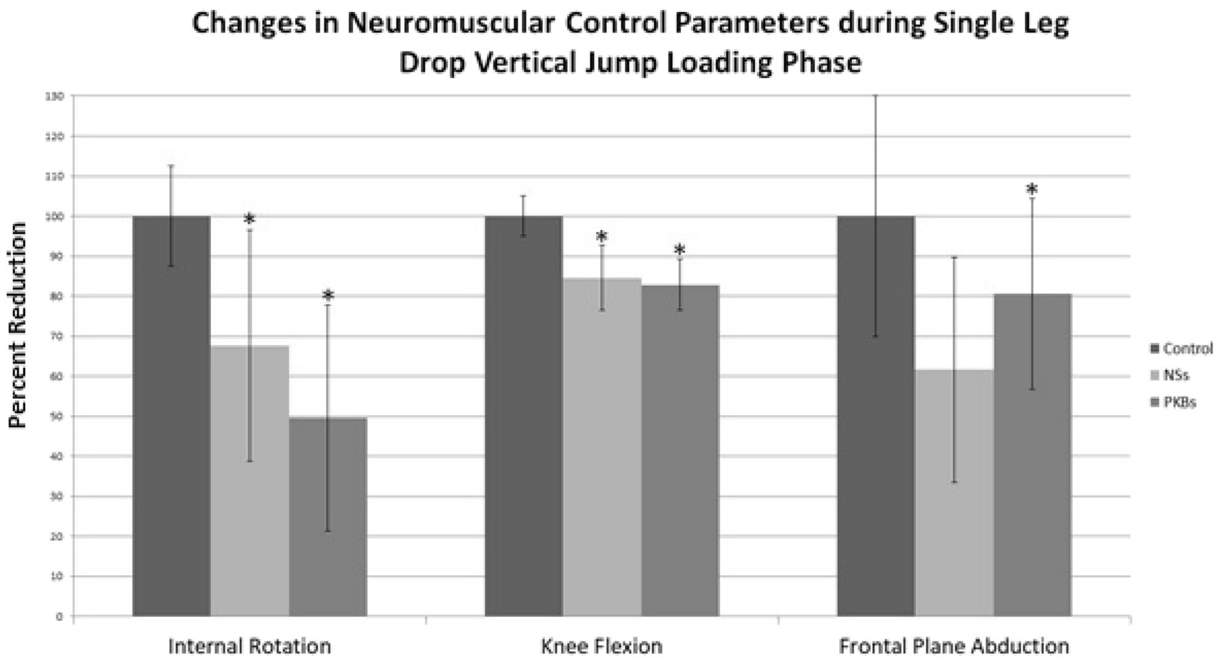

Fig. 3. Percentages of unbraced neuromuscular control parameters with the use of NSs and PKBs during the single leg drop vertical jump loading phase (SLDVJ-L) compared to controls. Values are expressed as mean ± SEM. (*p < 0.05, as compared to control).

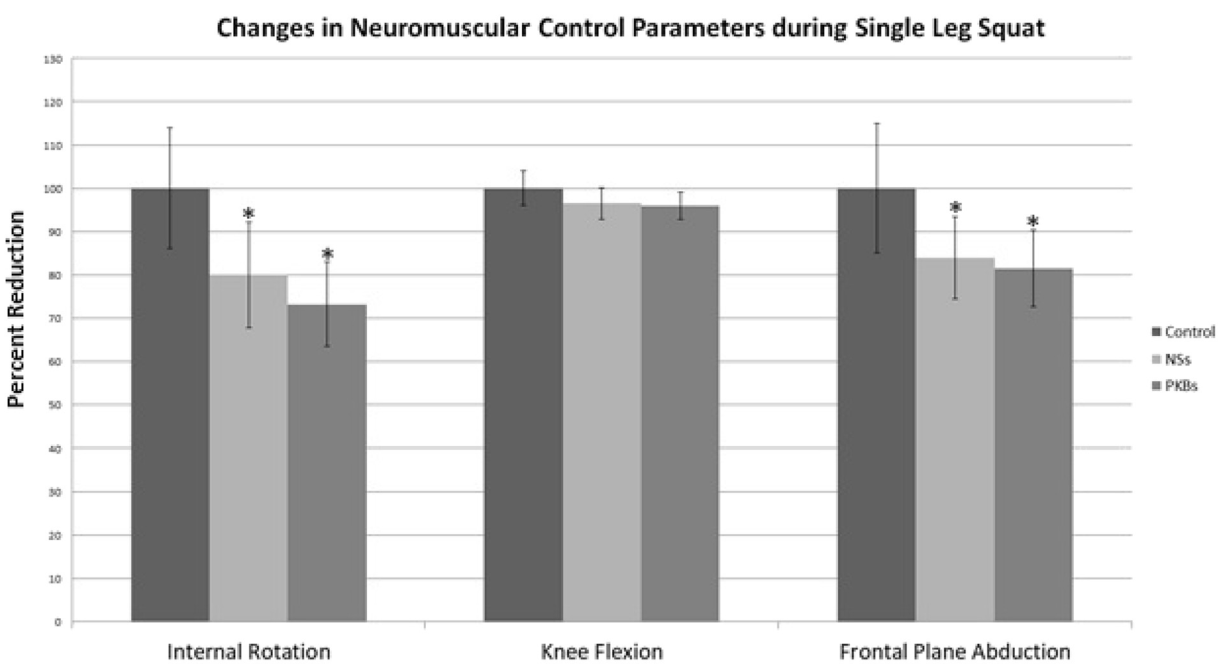

Fig. 4. Percentages of unbraced neuromuscular control parameters with the use of NSs and PKBs during the single leg squat (SLS) compared to control conditions. Values are expressed as mean ± SEM. (*p < 0.05, as compared to control).

no statistically significant differences in time required to complete the cutting maneuver with either NSs or PKBs. This indicates there is no decrease in cutting agility due to NSs or PKBs. Similarly, Sinclair, Vincent, and Richards found no difference in cutting performance, as measured by ground reactive forces, with or without PKB (Sinclair, Vincent, & Richards, 2017). In contrast, Rishiraj et al. (2011) found a decrease in initial athletic performance when bracing healthy individuals with eventual acclimation back to unbraced performance (Rishiraj et al., 2011). However, they examined agility in regards to straight-line sprint time and did not assess cutting. Furthermore, their observed decrease in performance was no longer observed after their subjects wore the brace for a mean of 14 h, which indicates that any change in performance may be temporary and related to acclimation. We did not observe an acclimation effect in this study, although this observation is limited given that we simply had each participant perform five cutting maneuvers per braced session for a total of 3 sessions on 3 separate days within a week. Greene et al. (2000) studied the effect

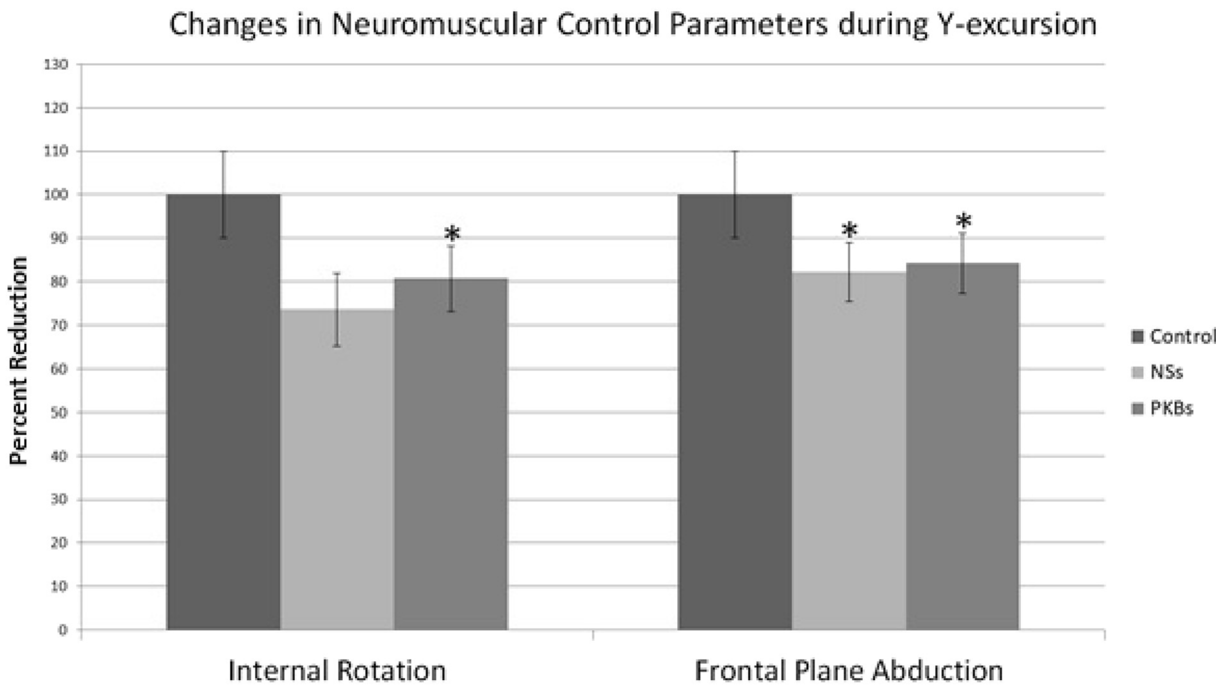

Fig. 5. Percentages of unbraced neuromuscular control parameters with the use of NSs and PKBs during the Y-excursion compared to controls. Values are expressed as mean ± SEM. (*$p < 0.05$, as compared to control).

of several different brands of knee braces on 40-yard dash and a four-cone agility drill, which involves cutting, and found that certain braces had no effect while others made times significantly slower (David L. Greene et al., 2000). Thus, our results may only apply to the braces used in this study.

Previous studies demonstrated that noncontact ACL injury is frequently associated with loading an extended knee (Boden et al., 2009; Koga et al., 2010; Britt Elin Øiestad et al., 2010), leading to maximal ACL length and strain (Beynnon et al., 1997; C.; Quatman & Hewett, 2009; Risberg et al., 2016; Sforzo et al., 1989; Shin et al., 2011). Our study demonstrates that knee flexion was minimally reduced for both NSs and PKBs compared to control (3.5%–4.0% during SLS and 15.4%–17.2% during SLDVJ). Although we found that NSs and PKBs reduced knee flexion, the benefit of reduced knee FPA may outweigh the negative effects of reduced knee flexion. This is because coronal and transverse plane kinematics may be far more important in the mechanism of noncontact ACL injuries than sagittal plane kinematics (McLean et al., 2004). Furthermore, Hangular et al. (2016) used a dynamic knee simulator of drop landings on a cadaveric model with and without bracing and found that the use of PKBs reduced strain in the ACL (Hangalur et al., 2016). Although their study utilized a cadaveric model, their findings suggest that future studies should directly examine ACL strain during dynamic activity with and without the use of NSs and PKBs.

4.1. Limitations

Our small sample size may limit the generalizability of our results. We also specifically recruited young, healthy subjects. Thus, their demographic characteristics may not reflect that of high-level elite athletes. Our research team used a novel markerless motion capture technology and its affiliated software to capture this data. Not all measurements by the DARI system have to date been fully validated. To use the DARI system, a skeleton model is fitted to the three-dimensional outline of each subject, as each subject directly faces the primary of 14 cameras to ascertain joint centers and axes. Typical osteokinematic measures use anthropometrics and bony landmarks to determine joint centers and axes, and this difference does not allow direct comparison of this system to others, especially with non-sagittal angles. Furthermore, the system used a proprietary processing step, which limits the reproducibility of our data with other systems. However, we created each subject's skeleton model with consistent methodology so relative measurements within this study should be reliable. We were also not able to measure tibial internal rotation relative to the femur with this system because the changes were too minute to be detected. An exact measure of knee internal rotation would have allowed us to better examine risk for noncontact ACL injury. We had also measured ground contact time and toe-off with manual video review. Although this method has been regularly used in the clinical setting, recently-developed methods using ground force plates may be more accurate (Muro-de-la-Herran, Garcia-Zapirain, & Mendez-Zorrilla, 2014). However, these methods were not available at our institution during the data collection period. Moreover, the hip joint is traditionally represented by the articulation between the pelvis and femur. However, the DARI system does not provide a pelvic segment, but rather a skeleton with a lower extremity that articulates with a spine. We also placed PKBs and NSs on a single side. As a result, our findings can not necessarily be extrapolated to instances where athletes wear braces on both knees (Salata et al., 2010). Furthermore, we only used braces from a single company, which may not reflect other commercially available braces. Finally, although our data suggest that NSs and PKBs may have a role in injury prevention by limiting potentially injury-provoking motions, this laboratory study was not designed to directly determine this role.

5. Conclusion

Our results demonstrate that NSs and PKBs significantly reduced hip internal rotation, knee flexion, and knee FPA during movements that required significant neuromuscular control without affecting cutting agility. Decreased hip internal rotation and FPA may decrease dynamic valgus of the knee and thereby may protect against noncontact ACL injury. Future studies should prospectively evaluate the role of NSs and PKBs in injury prevention with a larger sample size and a more diverse group of subjects. Furthermore, the long-term effects of knee bracing on adjacent joints and knee biomechanics are unknown and need further study.

Ethical approval

This study was approved by the University of Missouri Health Care Institutional Review Board and all volunteers provided informed consent. Privacy and rights of the subjects were protected.

Conflicts of interest

None.

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References

Albright, J., Powell, J., Smith, W., Martindale, A., Crowley, E., Monroe, J., et al. (1994). Medial collateral ligament knee sprains in college football effectiveness of preventive braces. *The American Journal of Sports Medicine, 22*, 12.

Baltaci, G., Aktas, G., Camci, E., Oksuz, S., Yildiz, S., & Kalaycioglu, T. (2011). The effect of prophylactic knee bracing on performance: Balance, proprioception, coordination, and muscular power. *Knee Surgery, Sports Traumatology, Arthroscopy, 19*, 1722–1728.

Beckett, M. E., Massie, D. L., Bowers, K. D., & Stoll, D. A. (1992). Incidence of hyperpronation in the ACL injured knee: A clinical perspective. *Journal of Athletic Training, 27*, 58–62.

Beynnon, B. D., Johnson, R. J., Fleming, B. C., Stankewich, C. J., Renström, P. A., & Nichols, C. E. (1997). The strain behavior of the anterior cruciate ligament during squatting and active flexion-extension: A comparison of an open and a closed kinetic chain exercise. *The American Journal of Sports Medicine, 25*, 823–829.

Boden, B. P., Torg, J. S., Knowles, S. B., & Hewett, T. E. (2009). Video analysis of anterior cruciate ligament injury: Abnormalities in hip and ankle kinematics. *The American Journal of Sports Medicine, 37*, 252–259.

Boutris, N., Byrne, R. A., Delgado, D. A., Hewett, T. E., McCulloch, P. C., Lintner, D. M., et al. (2018). Is there an association between noncontact anterior cruciate ligament injuries and decreased hip internal rotation or radiographic femoroacetabular impingement? A systematic review. *Arthroscopy: The Journal of Arthroscopic & Related Surgery, 34*, 943. Official publication of the Arthroscopy Association of North America and the International Arthroscopy Association.

Budini, K., Richards, J., Cole, T., Trede, R., George, L., Selfe, J., et al. (2018). An exploration of the use of Inertial Measurement Units in the assessment of dynamic postural control of the knee and the effect of bracing and taping. *Physiotherapy Practice and Research, 39*, 91–98.

Cochrane, J. L., Lloyd, D. G., Besier, T. F., Elliott, B. C., Doyle, T. L. A., & Ackland, T. R. (2010). Training affects knee kinematics and kinetics in cutting maneuvers in sport. *Medicine & Science in Sports & Exercise, 42*, 1535–1544.

Corazza, S., Mündermann, L., Chaudhari, A., Demattio, T., Cobelli, C., & Andriacchi, T. (2006). A markerless motion capture system to study musculoskeletal biomechanics: Visual hull and simulated annealing approach. *Annals of Biomedical Engineering, 34*, 1019–1029.

Erickson, A., Yasuda, K., Beynnon, B., Johnson, R., & Pope, M. (1993). An in vitro dynamic evaluation of prophylactic knee braces during lateral impact loading. *The American Journal of Sports Medicine, 21*, 26–35.

Fischer, K. M., Willwacher, S., Arndt, A., & Brüggemann, G. (2018). Calcaneal adduction and eversion are coupled to talus and tibial rotation. *Journal of Anatomy, 233*, 64–72.

Giotis, D., Paschos, N., Zampelis, F., Pappas, E., Mitsionis, G., & Georgoulis, A. (2016). Bracing can partially limit tibial rotation during stressful activities after anterior crucial ligament reconstruction with a hamstring graft. *Orthopaedics and Traumatology: Surgery & Research, 102*, 601–606.

Giotis, D., Tsiaras, V., Ristanis, S., Zampeli, F., Mitsionis, G., Stergiou, N., et al. (2011). Knee braces can decrease tibial rotation during pivoting that occurs in high demanding activities. *Knee Surgery, Sports Traumatology, Arthroscopy, 19*, 1347–1354.

Grace, T., Skipper, B., Newberry, J., Nelson, M., Sweetser, E., & Rothman, M. (1988). Prophylactic knee braces and injury to the lower extremity. *The Journal of Bone and Joint Surgery, 70-A*, 422–427.

Greene, D. L., Hamson, K. R., Curtis Bay, R., & Bryce, C. D. (2000). Effects of protective knee bracing on speed and agility. *The American Journal of Sports Medicine, 28*, 453–459.

Hangalur, G., Brenneman, E., Nicholls, M., Bakker, R., Laing, A., & Chandrashekar, N. (2016). Can a knee brace reduce the strain in the anterior cruciate ligament? A study using combined in vivo/in vitro method. *Prosthetics and Orthotics International, 40*, 394–399.

Hanzlíková, I., Richards, J., Hébert-Losier, K., & Smékal, D. (2019). The effect of proprioceptive knee bracing on knee stability after anterior cruciate ligament reconstruction. *Gait & Posture, 67*, 242–247.

Hanzlíková, I., Richards, J., Tomsa, M., Chohan, A., May, K., Smékal, D., et al. (2016). The effect of proprioceptive knee bracing on knee stability during three different sport related movement tasks in healthy subjects and the implications to the management of Anterior Cruciate Ligament (ACL) injuries. *Gait & Posture, 48*, 165–170.

Harris, G., & Wertsch, J. (1994). Procedures for gait analysis. *Archives of Physical Medicine and Rehabilitation, 75*, 216–225.

Havens, K., & Sigward, S. (2015). Cutting mechanics: Relation to performance and anterior cruciate ligament injury risk. *Medicine & Science in Sports & Exercise, 47*, 818–824.

Herzog, M., Marshall, S., Lund, J., Pate, V., & Spang, J. (2017). Cost of outpatient Arthroscopic anterior cruciate ligament reconstruction among commercially insured patients in the United States, 2005-2013. *Orthopaedic Journal of Sports Medicine, 5*, 1–8.

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., et al. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *The American Journal of Sports Medicine, 33*, 492–501.

Hewett, T. E., Paterno, M. V., & Myer, G. D. (2002). Strategies for enhancing proprioception and neuromuscular control of the knee. *Clinical Orthopaedics and Related Research, 402*, 76–94.

Kimura, Y., Ishibashi, Y., Tsuda, E., Yamamoto, Y., Tsukada, H., & Toh, S. (2010). Mechanisms for anterior cruciate ligament injuries in badminton. *British Journal of Sports Medicine, 44*, 1124–1127.

Knippenberg, E., Verbrugghe, J., Lamers, I., Palmaers, S., Timmermans, A., & Spooren, A. (2017). Markerless motion capture systems as training device in neurological rehabilitation: A systematic review of their use, application, target population and efficacy. *Journal of Neuroengineering and Rehabilitation, 14*, 61-11.

Knowles, S. B., Marshall, S. W., Miller, T., Spicer, R., Bowling, J. M., Loomis, D., et al. (2007). Cost of injuries from a prospective cohort study of North Carolina high school athletes. *Injury Prevention : Journal of the International Society for Child and Adolescent Injury Prevention, 13*, 416–421.

Koga, H., Nakamae, A., Shima, Y., Iwasa, J., Myklebust, G., Engebretsen, L., et al. (2010). Mechanisms for noncontact anterior cruciate ligament injuries: Knee joint kinematics in 10 injury situations from female team handball and basketball. *The American Journal of Sports Medicine, 38*, 2218–2225.

Krosshaug, T., Nakamae, A., Boden, B. P., Engebretsen, L., Smith, G., Slauterbeck, J. R., et al. (2007). Mechanisms of anterior cruciate ligament injury in basketball: Video analysis of 39 cases. *The American Journal of Sports Medicine, 35*, 359–367.

Liggett, C., Tandy, R., & Young, J. (1995). The effects of prophylactic knee bracing on running gait. *Journal of Athletic Training, 30*, 159–161.

McLean, S. G., Huang, X., Su, A., Bogert, van den, & Antonie, J. (2004). Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. *Clinical Biomechanics, 19*, 828–838.

Moon, J., Kim, H., Lee, J., & Panday, S. (2018). Effect of wearing a knee brace or sleeve on the knee joint and anterior cruciate ligament force during drop jumps: A clinical intervention study. *The Knee, 25*, 1009–1015.

Mortaza, N., Ebrahimi, I., Ashraf Jamshidi, A., Abdollah, V., Kamali, M., Bakar Wan Abas, W. A., et al. (2012). The effects of a prophylactic knee brace and two neoprene knee sleeves on the performance of healthy athletes: A crossover randomized controlled trial. *PLoS One, 7*. e50110.

Muro-de-la-Herran, A., Garcia-Zapirain, B., & Mendez-Zorrilla, A. (2014). Gait analysis methods: An overview of wearable and non-wearable systems, highlighting clinical applications. *Sensors, 14*, 3362–3394.

Najibi, S., & Albright, J. P. (2005). The use of knee braces, Part 1: Prophylactic knee braces in contact sports. *The American Journal of Sports Medicine, 33*, 602–611.

Øiestad, B. E., Holm, I., Aune, A. K., Gunderson, R., Myklebust, G., Engebretsen, L., et al. (2010). Knee function and prevalence of knee osteoarthritis after anterior cruciate ligament reconstruction: A prospective study with 10 to 15 years of follow-up. *The American Journal of Sports Medicine, 38*, 2201–2210.

Øiestad, B., Holm, I., Engebretsen, L., Aune, A., Gunderson, R., & Risberg, M. (2013). The prevalence of patellofemoral osteoarthritis 12 years after anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy, 21*, 942–949.

Olsen, O., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball: A systematic video analysis. *The American Journal of Sports Medicine, 32*, 1002–1012.

Perrott, M., Pizzari, T., Cook, J., & McClelland, J. (2016). Comparison of lower limb and trunk kinematics between markerless and marker-based motion capture systems. *Gait & Posture, 52*, 57–61.

Powers, C. M. (2003). The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: A theoretical perspective. *Journal of Orthopaedic & Sports Physical Therapy, 33*, 639–646.

Quatman, C., & Hewett, T. (2009). The anterior cruciate ligament injury controversy:

Is ‘‘valgus collapse’’ a sex-specific mechanism? *British Journal of Sports Medicine, 43*, 328–335.
Quatman, C., Quatman-Yates, C., & Hewett, T. (2010). A ‘plane’ explanation of anterior cruciate ligament injury mechanisms. *Sports Medicine, 40*, 729–746.
Risberg, M. A., Oiestad, B. E., Gunderson, R., Aune, A. K., Engebretsen, L., Culvenor, A., et al. (2016). Changes in knee osteoarthritis, symptoms, and function after anterior cruciate ligament reconstruction: A 20 year prospective follow-up study. *The American Journal of Sports Medicine, 44*, 1215–1224.
Rishiraj, N., Taunton, J., Lloyd-Smith, R., Regan, W., Niven, B., & Woollard, R. (2011). Effect of functional knee brace use on acceleration, agility, leg power and speed performance in healthy athletes. *British Journal of Sports Medicine, 45*, 1230–1237.
Rishiraj, N., Taunton, J., Lloyd-Smith, R., Woollard, R., Regan, W., & Clement, D. (2009). The potential role of prophylactic/functional knee bracing in preventing knee ligament injury. *Sports Medicine, 39*, 937–960.
Salata, M. J., Gibbs, A. E., & Sekiya, J. K. (2010). The effectiveness of prophylactic knee bracing in American football: A systematic review. *Sport Health, 2*, 375–379.
Sandau, M., Koblauch, H., Moeslund, T., Aanæs, H., Alkjæra, T., & Simonsen, E. (2014). Markerless motion capture can provide reliable 3D gait kinematics in the sagittal and frontal plane. *Medical Engineering & Physics, 36*, 1168–1175.
Schmitz, R. J., Shultz, S. J., & Nguyen, A. (2009). Dynamic valgus alignment and functional strength in males and females during maturation. *Journal of Athletic Training, 44*, 26–32.
Schmitz, A., Ye, M., Boggess, G., Shapiro, R., Yang, R., & Noehren, B. (2015). The measurement of in vivo joint angles during a squat using a single camera markerless motion capture system as compared to a marker based system. *Gait & Posture, 41*, 694–698.
Schmitz, A., Ye, M., Shapiro, R., Yang, R., & Noehren, B. (2013). Accuracy and repeatability of joint angles measured using a single camera markerless motion capture system. *Journal of Biomechanics, 47*, 587–591.
Sforzo, G., Chen, N., Gold, C., & Frye, P. (1989). The effect of prophylactic knee bracing on performance. *Medicine & Science in Sports & Exercise, 21*, 254–257.
Shields, R. K., Madhavan, S., Gregg, E., Leitch, J., Petersen, B., Salata, S., et al. (2005). Neuromuscular control of the knee during a resisted single-limb squat exercise. *The American Journal of Sports Medicine, 33*, 1520–1526.
Shin, C. S., Chaudhari, A. M., & Andriacchi, T. P. (2011). Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone. *Medicine & Science in Sports & Exercise, 43*, 1484–1491.
Sinclair, J., Vincent, H., & Richards, J. (2017). Effects of prophylactic knee bracing on knee joint kinetics and kinematics during netball specific movements. *Physical Therapy in Sport, 23*, 93–98.
Sitler, M., Ryan, C. J., Hopkinson, L. W., Wheeler, L. J., Santomier, J., Kolb, L. R., et al. (1990). The efficacy of a prophylactic knee brace to reduce knee injuries in football: A prospective, randomized study at West Point. *The American Journal of Sports Medicine, 18*, 310–315.
Théoret, D., & Lamontagne, M. (2006). Study on three-dimensional kinematics and electromyography of ACL deficient knee participants wearing a functional knee brace during running. *Knee Surgery, Sports Traumatology, Arthroscopy, 14*, 555–563.
Tiberio, D. (1987). The effect of excessive subtalar joint pronation on patellofemoral mechanics: A theoretical model. *Journal of Orthopaedic & Sports Physical Therapy, 9*, 160–165.
Wang, D., Bakhai, A., Del Buono, A., & Maffulli, N. (2013). Sample size determination for clinical research. *Muscles, Ligaments, and Tendons Journal, 3*, 116–117.