

Central Lancashire Online Knowledge (CLOK)

Title	Effects of a prophylactic knee sleeve on anterior cruciate ligament and lower extremity biomechanics: an examination using musculoskeletal simulation
Type	Article
URL	https://clock.uclan.ac.uk/id/eprint/40349/
DOI	https://doi.org/10.1142/s021951942250018x
Date	2022
Citation	Sinclair, Jonathan Kenneth, Grimshaw, Niamh, Latham, Owen, Taylor, Paul John and Nachiappan, Chockalingam (2022) Effects of a prophylactic knee sleeve on anterior cruciate ligament and lower extremity biomechanics: an examination using musculoskeletal simulation. Journal of Mechanics in Medicine and Biology. ISSN 0219-5194
Creators	Sinclair, Jonathan Kenneth, Grimshaw, Niamh, Latham, Owen, Taylor, Paul John and Nachiappan, Chockalingam

It is advisable to refer to the publisher's version if you intend to cite from the work.
<https://doi.org/10.1142/s021951942250018x>

For information about Research at UCLan please go to <http://www.uclan.ac.uk/research/>

All outputs in CLOK are protected by Intellectual Property Rights law, including Copyright law. Copyright, IPR and Moral Rights for the works on this site are retained by the individual authors and/or other copyright owners. Terms and conditions for use of this material are defined in the <http://clock.uclan.ac.uk/policies/>

1 **Effects of a prophylactic knee sleeve on anterior cruciate ligament and lower extremity**
2 **biomechanics: an examination using musculoskeletal simulation.**

3 *Jonathan Sinclair¹, Niamh Grimshaw¹, Owen Latham¹, Paul John Taylor², Nachiappan*
4 *Chockalingam³*

5 1. Research Centre for Applied Sport, Physical Activity and Performance, School of
6 Sport & Health Sciences, Faculty of Allied Health and Wellbeing, University of
7 Central Lancashire, Lancashire, UK.

8 2. School of Psychology, Faculty of Science & Technology, University of Central
9 Lancashire, Lancashire, UK.

10 3. School of Life Sciences and Education, Staffordshire University, City of Stoke, Stoke
11 on Trent, UK.

12 **Correspondence Address:**

13 Dr. Jonathan Sinclair
14 University of Central Lancashire
15 Preston
16 Lancashire
17 PR1 2HE

18 **e-mail:** jksinclair@uclan.ac.uk

19 **Keywords:** biomechanics; anterior cruciate ligament; kinematics; knee sleeve; simulation.

21 **Abstract**

22 The current study aimed using a two-experiment musculoskeletal simulation-based approach,
23 measuring ACL biomechanics, knee joint kinematics and lower extremity joint loading to
24 examine the effects of both a prophylactic knee sleeve on 1. a sport specific change of direction
25 movement in female footballers and 2. a single leg landing in male footballers. **Experiment 1**

examined 12 female university first team level footballers (age 20.2 ± 1.34 years, height 1.61 ± 0.06 m, body mass 57.2 ± 5.6 kg) undertaking a 45° cutting movement in sleeve and no-sleeve conditions. Experiment 2 examined 10 male university first team level footballers (age 21.1 ± 1.13 years, height 1.77 ± 0.1 m, body mass 71.9 ± 8.6 kg) undertaking a single leg drop jump landing in sleeve and no-sleeve conditions. In each experiment, data was collected in a biomechanics laboratory and three-dimensional motion capture and ground reaction force information was collected. Three-dimensional kinematics, three-dimensional knee kinetics and ACL ligament forces/ strains were measured using musculoskeletal simulation, and participants were also asked to subjectively rate the knee sleeve in terms of both comfort and stability. Experiment 1 showed that the sleeve condition was associated with greater ACL strain (sleeve = 13.57% and no-sleeve = 10.26%) and forces (sleeve = 1.19BW and no-sleeve = 0.94BW). In addition, the brace condition also enhanced lateral compressive tibiofemoral (sleeve = 4.70BW and no-sleeve = 4.20BW) and total compressive tibiofemoral force (sleeve = 11.73BW and no-sleeve = 11.08BW). Finally, for the subjective ratings, participants indicated that the knee sleeve significantly improved perceived comfort and stability. Experiment 2 did not reveal any statistical differences between knee sleeve and no-sleeve conditions, nor any effects of the knee sleeve on subjective ratings of comfort or stability. Therefore, the findings from the current investigation suggest that the prophylactic knee sleeve examined in the current investigation does not appear to reduce the biomechanical parameters linked to the aetiology of knee pathologies in male/ female footballers.

Introduction

Football is regarded as the most popular sport in terms of audience and participants, with more than 200,000 professional and over 240 million amateur players globally ¹. Football like most other team sports is characterized by intermittent deceleration and landing activities requiring

rapid and agile change of direction movements ². As both a competitive and recreational activity, football is associated with a plethora of physical benefits including enhanced cardiovascular, mental and bone health ³. However, football is also connected with a relatively high incidence of injury ⁴, which has been shown to exert a significant burden on socioeconomic and healthcare systems ⁵. Epidemiological investigations in professional players have shown injury rates of 8.0 per 1000 h and an average of 2.0 injuries per season ⁶ and 38.56 per 1000 h, at a rate of 0.85 time-loss injuries per match in recreational players ⁷.

One of the most commonly injured musculoskeletal structures in football is the knee ^{6,7}, and the anterior cruciate ligament (ACL) is the most frequently injured knee ligament ⁸. The ACL itself is vital for the provision of knee stability during the dynamic activities associated with football ⁹. With its unique functional properties, attachment points and complex anatomy, the ACL is highly effective in restraining both excessive anterior tibial translation and coronal/transverse plane knee motions ¹⁰. ACL injuries in football players are predominantly, non-contact in nature, in that the ligament becomes injured without physical contact between players ¹¹.

Physiologically, ACL injuries occur when the ligament experiences excessive tensile forces and strains ¹². As the ACL serves primarily to resist anteriorly directed tibial translation in addition to knee valgus and internal/ external rotation movements; in vivo and in vitro investigations have shown that it experiences both load and strain during activities that involve these mechanisms ¹³. Aetiological investigations support this, in that the ACL is most commonly disrupted in the period immediately following foot contact, in athletic tasks involving sudden decelerations, landings and cutting manoeuvres ¹⁴. Injury to the ACL is

extremely serious in competitive players, and typically leads to long term absence from football¹⁵. ACL pathologies typically require reconstructive intervention using auto/allografts in order to provide sufficient stability to the injured knee to allow return to training/ competitive activities^{16, 17}. Silvers & Mandelbaum¹⁸ showed that over 250,000 ACL reconstruction interventions are undertaken each year in the US alone with average allocated costs exceeding \$2 billion.

Importantly, the ACL can be associated with poor healing capacity, and the risk of a second injury is as high as 30% in the ipsilateral knee and 11% in the contralateral side^{19, 20}. Even after full recovery, ACL injuries frequently lead to chronic knee pain, and athletes who experience an ACL pathology are up to ten times more susceptible to early-onset degenerative knee osteoarthritis²¹, leading not only to a decline in athletic participation but also enduring disability in later life²². Radiographic knee osteoarthritis significantly reduces health-related quality of life, and degenerative joint disease secondary to ACL injury imposes further economic burden²³. Similarly, it has been demonstrated that psychological as well as physical wellbeing is negatively affected, and ACL injuries have been associated with anxiety, self-esteem, pain response, depression, and feelings of decreased athletic identity²⁴. Importantly, previous analyses have shown that many footballers fail to return to their previous levels of athletic function, as statistically significant performance decrements have been observed in relation to non-injured controls²⁵. Concerningly, both Roos et al.,²⁶ and Walden et al.,¹⁵ demonstrated that only 30-35% of competitive footballers remained active 3 years after suffering an ACL injury.

Because of the high incidence of ACL injuries in football players¹⁵ and the poor-long term prognosis following injury, prophylactic interventions are therefore a key clinical priority²⁷. Knee braces are external devices constructed in order to improve three-dimensional knee joint dynamic alignment²⁸ and range from semi-rigid devices incorporating uni or polyaxial hinges to more compliant sleeves designed simply to provide compression and enhance proprioception²⁹. Knee braces represent a conservative and relatively low-cost external apparatus that are minimally invasive/ restrictive such that they can be worn during high-intensity sports maneuvers²⁸. Prophylactic knee braces have been shown to reduce transverse plane knee range of motion during run, cut and vertical jump movements in netball players²⁸, peak knee adduction moment during a badminton lunge³⁰ and patellar tendon loading in run, cut and single leg hop movements in female athletes³¹. Furthermore, Sinclair et al.³² showed using an inverse dynamics-based method of quantifying ligament loading, that ACL load rates were significantly reduced during single leg hop landings and cut movements.

However, the efficacy of any intervention modality depends on a sound comprehension of the underlying causative mechanisms of the associated condition. Inverse dynamics represent only global indices of joint loading, and therefore, are not truly representative of localized loading experienced by the joint structures³³. Herzog et al.³⁴ showed that muscles are the primary contributors to the forces experienced by the lower extremity joint structures. Specifically, the complex role of muscles in controlling knee ligament loading during human movement has received insufficient attention within the literature, owing to difficulties in calculating muscle kinetics and modelling knee joint ligamentous structures²⁷. To date, there has yet to be any investigation which has examined the effects of prophylactic knee bracing on ligament load and strain parameters linked to the aetiology of ACL using a muscle driven approach to

quantify knee mechanics. This is principally due to the inability to non-invasively quantify ACL loads and strains during high-risk sports movements³⁵.

Recent, advances in musculoskeletal simulation software alongside enhancements in simulation model algorithmic complexity, mean that quantitative indices of ACL kinetics and strains are now attainable alongside more traditional simulation parameters of joint and muscle forces³⁶. To date however, this more advanced modelling approach has not yet been utilized to explore the effects of prophylactic knee sleeves on ACL loading and strain during high-risk sports specific football movements. Similarly, whilst the effects of prophylactic knee sleeve have been examined previously, they have focused only on indices of knee joint loading/kinematics. Knee sleeves are likely to mediate both kinetic and kinematic alterations at more than one body segment and thus at more than one joint; and potential positive alterations at the knee joint mediated via the sleeve, may cause concurrent effects at other lower extremity joints. Therefore, a more comprehensive approach also examining hip and ankle joint loading in addition to knee joint kinetics would be of both practical and clinical relevance.

To summarize, there is currently no scientific investigation that has explored the effects of prophylactic knee bracing on collective indices of ACL loading/ strains alongside lower extremity joint loading using musculoskeletal simulation in football players. Therefore, the aims of the current study were, using a two-experiment musculoskeletal simulation-based approach (whilst measuring ACL biomechanics, knee joint kinematics and lower extremity joint loading) to examine the effects of both a prophylactic knee sleeve on 1. a sport specific cutting movement in female university level footballers and 2. a single leg landing in male university footballers. A study of this nature may provide further insight into the

comprehensive biomechanical effects of prophylactic knee sleeve designed to reduce the risk from knee pathologies in football players.

Methods

For both investigations, participants provided written informed consent and ethical approval was obtained from the University of Central Lancashire, in accordance with the principles documented in the Declaration of Helsinki. All participants were free from lower extremity musculoskeletal pathology at the time of data collection and had not undergone surgical intervention at the knee joint.

Knee sleeve

A single nylon/silicone knee sleeve (Figure 1) was utilized in this investigation, (Kuangmi 1 PC compression knee sleeve), was used in this study which came in three different sizes; small, medium and large to accommodate all participants and was worn on the dominant (right) limb in all participants. In accordance with Sinclair et al.,²⁸, at the end of data collection participants were asked to subjectively rate the knee sleeve in relation to performing the movements without the sleeve in terms of stability and comfort. This was accomplished using 3-point scales that ranged from 1 = increased comfort, 2 = no-change and 3 = reduced comfort and 1 = increased stability, 2 = no change and 3 = increased stability.

@@@FIGURE 1 NEAR HERE@@@

Experiment 1

Participants

Twelve female (age 20.2 ± 1.34 years, height 1.61 ± 0.06 m, body mass 57.2 ± 5.6 kg and BMI = 22.1 ± 3.0 kg/m²) university first team level footballers volunteered to take part in the current investigation.

Procedure

Participants completed five trials of a 45° cut movement in both experimental conditions (sleeve and no-sleeve). Data collection was undertaken in 22 m long biomechanics laboratory, using an **a-priori** approach velocity of 4.0 ± 0.2 m/s striking the force platform with their right (dominant) limb. **Cut angles were measured from the centre of the force platform and the corresponding line of movement was delineated using masking tape so that it was clearly evident to participants (Figure 2).** The stance phase of the cut movement was defined as the duration over > 20 N of vertical force applied to the force platform.

@@@FIGURE 2 NEAR HERE@@@

The order in which participants performed in each knee sleeve condition was counterbalanced i.e. participant 1 performed first in the knee sleeve condition followed by the no-sleeve condition whereas participant 2 was examined first in the no-sleeve condition followed by the knee sleeve and so on and so forth. To ensure consistency, each participant wore the same footwear (Asics, Patriot 6). **Kinematic information was obtained using an eight-camera wall mounted motion analysis system (Qualisys Medical AB, Goteburg, Sweden) with a capture frequency of 250 Hz. The camera system was arranged in an umbrella-based configuration and covered an 8 m length and 6 m width (Figure 2).** To measure ground reaction forces (GRF), an embedded piezoelectric force platform (Kistler National Instruments, Model 9281CA)

operating at 1000 Hz was adopted. The GRF and kinematic information were synchronously obtained using an analogue board and interfaced using Qualisys track manager.

To define the anatomical frames of the thorax, pelvis, thighs, shanks and feet, passive retroreflective markers of 19mm diameter were placed at the C7, T12 and xiphoid process landmarks and also positioned bilaterally onto the acromion process, iliac crest, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanter, calcaneus, first metatarsal and fifth metatarsal (Figure 3a). The hip, knee and ankle joint centre's were delineated according to previously established guidelines³⁷⁻³⁹. Carbon-fibre tracking clusters comprising of four non-linear retroreflective markers were positioned onto the thigh and shank segments. The foot segments were tracked via the calcaneus, first and fifth metatarsal, the pelvic segment using the PSIS and ASIS markers and the thorax via the T12, C7 and xiphoid markers. Static calibration trials were obtained with the participant in the anatomical position in order for the positions of the anatomical markers to be referenced in relation to the tracking clusters/markers, following which those not required for dynamic data were removed. The Z (transverse) axis was oriented vertically from the distal segment end to the proximal segment end. The Y (coronal) axis was oriented in the segment from posterior to anterior. Finally, the X (sagittal) axis orientation was determined using the right-hand rule and was oriented from medial to lateral (Figure 3b).

@@@FIGURE 3 NEAR HERE@@@

Furthermore, the effects of the prophylactic sleeve on knee joint proprioception were investigated via a weight-bearing knee joint position sense test. In accordance with the

procedure of Sinclair et al.²⁹, (with all of the above-mentioned retroreflective markers remaining in place) participants stood in the centre of the motion capture system volume, on one leg using the dominant limb. They then slowly squatted to a knee flexion angle of 30°, which was verified using a handheld goniometer via same researcher throughout the testing process. This position was held for a period of 15 s during which time the knee ‘criterion’ angle was captured using the motion capture system (Figure 4ab). Following this, participants were asked to return to a standing (i.e. with both feet on the floor) position for a further 15 s, and then repeated the above process without guidance from the goniometer; a condition henceforth named ‘unaided’. This position was again held for a period of 15 s and the unaided trial was similarly collected using the motion analysis system. This above process was undertaken on three occasions in both prophylactic sleeve and no-sleeve conditions using a counterbalanced order, and in between each trial participants walked a fixed distance of 20 ft to eliminate proprioceptive memory of the previous trial.

@@@FIGURE 4 NEAR HERE@@@

Data Processing

Dynamic and proprioception trials were digitized using Qualisys Track Manager (Qualisys Medical AB, Goteburg, Sweden) in order to identify anatomical and tracking markers then exported as C3D files to Visual 3D (C-Motion, Germantown, MD, USA). GRF data and marker trajectories were smoothed with cut-off frequencies of 50 Hz at 12 Hz respectively, using a low-pass Butterworth 4th order zero lag filter. Within Visual 3D knee joint angles were quantified using an XYZ cardan sequence (where X is the sagittal plane; Y is the coronal plane and is Z is the transverse plane).

For the proprioceptive data, the knee flexion angle during the criterion and unaided trials was calculated. The absolute difference in the knee flexion angle in degrees, was calculated between the criterion and unaided trials to provide an proprioception angular error value for both the prophylactic knee sleeve and no-sleeve conditions (with a low value indicates greater knee proprioception) and then extracted for statistical analysis. For dynamic trials obtained during the 45° cut movements, these were linearly normalized to 100 % of the stance phase. Three-dimensional angular kinematic measures from the stance phase that were extracted from the knee joint in each of the angular planes of rotation were peak angle, peak angular velocity and minimum angular velocity.

Dynamic data during the stance phase was exported from Visual 3D into OpenSim 3.3 software (Simtk.org) using a custom pipeline that allowed the inverse kinematics to be exported to match the degrees of freedom associated with the experimental model in OpenSim²⁷. The standard Gait2392 Opensim musculoskeletal model was adapted to include six degrees of freedom knee joints and also an ACL bundles modelled in accordance with Sinclair et al.,²⁷ as non-linearly elastic passive soft tissues based on the proximal (femur) and distal (tibia) insertion points of Xu et al.,⁴⁰ (Figure 5ab). The model was further developed by incorporating a patella and the tibiofemoral joint was separated into medial and lateral compartment locations which were positioned at 25% and 75% of the scaled knee joint width in accordance with Barrios & Willson⁴¹.

@@@FIGURE 5 NEAR HERE@@@

The model was firstly scaled within OpenSim to account for the anthropometrics of each participant, using data from the anatomical landmarks collected during the static calibration

269 trials. In accordance with Kar & Quesada,³⁵, muscle and ligament dimensions were scaled in
270 the same manner as body segments, from the static trial marker positions. Following this as
271 muscle forces are the main determinant of joint forces³⁴, muscle kinetics were quantified using
272 computed muscle control (CMC) procedure to estimate a set of muscle force patterns allowing
273 the model to replicate the required kinematics.

274
275 Then, three-dimensional ankle, medial tibiofemoral, lateral tibiofemoral and hip joint forces as
276 well as compressive patellofemoral joint forces were calculated via the joint reaction analyses
277 function within OpenSim, using the muscle forces generated from the CMC process as inputs.
278 The joint reaction analysis function in OpenSim calculates the joint loads transferred between
279 two contacting bodies, about the joint location identified during the static trial. Furthermore,
280 the three-dimensional forces calculated at the lateral and medial aspects of the tibiofemoral
281 joint via the joint reaction analysis were added together in order to also determine the total
282 tibiofemoral joint force in all three planes. In the current investigation, joint forces were
283 normalized by dividing by each participants body weight (BW).

284
285 From the above processing, peak three-dimensional ankle, lateral tibiofemoral, medial
286 tibiofemoral, total tibiofemoral and hip joint forces, and peak compressive patellofemoral
287 forces during the stance phase were extracted for statistical analyses. In addition, instantaneous
288 load rates (BW/s) for each of the aforementioned joint loads were extracted by obtaining the
289 peak increase in force between adjacent data points and joint force impulses (BW·ms) during
290 the stance phase were also calculated using a trapezoidal function.

291
292 In addition to the above, from the CMC process firstly the peak ACL force during the stance
293 phase was extracted and normalized by dividing the net values by bodyweight (BW).

Furthermore, the peak forces (BW) during the stance phase for the major muscles crossing the knee joint were quantified and also the muscle force impulses (BW·ms) during the stance phase were also extracted using a trapezoidal function. In addition, the biceps femoris long head, biceps femoris short head, semitendinosus, semimembranosus muscle forces calculated via the CMC process were added together to create the total hamstring muscle force. In addition, the rectus femoris, vastus lateralis, vastus medialis and vastus intermedius forces calculated via the CMC process were also summed to create the total quadriceps muscle force. The maximum total hamstring and total quadriceps forces as well as their impulses during the stance phase were extracted for statistical analysis.

In addition, the maximum ACL strain (%) was calculated by dividing the maximum ligament bundle length during the dynamic trials by the resting length, which was obtained during the static calibration trials³⁵ and ACL strain rate (%/s) was by obtaining the peak increase in ACL strain between adjacent data points.

Statistical analyses

For each parameter/ condition, means and standard deviations were calculated and differences between knee sleeve and no-sleeve conditions examined using Bayesian paired t-tests with default prior scales using SPSS 27.0 software (SPSS, IBM). Bayesian factors (BF) were used to explore the extent to which the data supported the alternative (H_1) hypothesis and Bayes factors throughout were interpreted in accordance with the recommendations of Jeffreys⁴² with values ≥ 3 indicating sufficient evidence in support of H_1 . In the interests of conciseness and clarity only variables that presented with Bayes factors ≥ 3 are presented in the results section. Finally, using the data collected from the subjective feedback based on participants' ratings of both stability and comfort were examined using Chi-Square tests.

319

320 Experiment 2

321 *Participants*

322 Ten male (age 21.1 ± 1.13 years, height 1.77 ± 0.1 m, body mass 71.9 ± 8.6 kg and BMI =
323 22.9 ± 3.2 kg/m²) university first team level footballers volunteered to take part in the current
324 investigation.

325

326 *Procedure*

327 Kinematic information was obtained using the procedure and biomechanical modelling
328 approach outlined in experiment 1 and participants once again wore the same footwear. For
329 this experiment participants performed single leg drop jump landings with their right
330 (dominant) limb after stepping off from a 30 cm plyometric box onto the force platform in
331 order to simulate deceleration phase of landing⁴³. The landing phase of was considered to have
332 begun at foot contact (defined as > 20 N of vertical force applied to the force platform) and
333 ended at the instance of maximum knee flexion.

334

335 *Processing*

336 The same processing techniques and variables as experiment 1 were adopted.

337

338 *Statistical analyses*

339 To examine biomechanical differences between conditions and subjective preferences/ ratings
340 the same statistical analyses as experiment 1 were adopted, with the same statistical principles
341 and reporting adhered to.

342

343 **Results**

344 Experiment 1

345 @@@ TABLE 1 NEAR HERE @@@

346 @@@ TABLE 2 NEAR HERE @@@

347 @@@ TABLE 3 NEAR HERE @@@

348
349 *Ligament biomechanics*

350 For the peak ACL strain, values were larger in the knee sleeve (BF = 4.45) condition compared
351 to no-sleeve (Table 1). For the peak ACL force, values were larger in the knee sleeve (BF =
352 25.53) condition compared to no-sleeve (Table 2).

353
354 *Joint loading*

355 For the hip shear force impulse values were larger in the knee sleeve (BF = 33.31) compared
356 to no-sleeve (Table 1). Furthermore, for the hip medial force impulse values were larger in the
357 knee sleeve (BF = 7.70) compared to no-sleeve (Table 1).

358
359 For the peak lateral tibiofemoral compressive force, values were larger in the knee sleeve (BF
360 = 28.55) conditions compared to no-sleeve (Table 1). For the peak total compressive
361 tibiofemoral force, values were greater in the knee sleeve (BF = 4.04) conditions compared to
362 no-sleeve (Table 1).

363
364
365 *Joint kinematics and proprioception*

366 No differences in joint kinematics or proprioception (BF <3.0) were observed (Table 2).

367
368 *Muscle forces*

For peak vastus medialis force, values were larger in the knee sleeve compared to no-sleeve (BF = 3.11) (Table 3). For peak gracilis force, values were larger in the no-sleeve condition compared to the knee sleeve (BF = 5.56) (Table 3). Similarly, for the gracilis force integral, values were larger in the no-sleeve condition compared to the knee sleeve (BF = 11.81) (Table 3).

Subjective ratings

For the subjective ratings, participants indicated that the sleeve significantly improved subjective comfort ($X^2_{(2)} = 13.50$, $p < 0.05$) and subjective stability ($X^2_{(2)} = 8.33$, $p < 0.05$).

Experiment 2

@@@ TABLE 4 NEAR HERE @@@

@@@ TABLE 5 NEAR HERE @@@

@@@ TABLE 6 NEAR HERE @@@

Ligament biomechanics

No differences in ligament biomechanics (BF <3.0) were observed (Table 4).

Joint loading

No differences in joint loading (BF <3.0) were observed (Table 4).

Joint kinematics and proprioception

No differences in joint kinematics or proprioception (BF <3.0) were observed (Table 5).

Muscle forces

No differences in muscle forces (BF <3.0) were observed (Table 6).

Subjective ratings

For the ratings of comfort, participants indicated that the sleeve did not significantly influence subjective comfort ($X^2_{(2)} = 1.75$, $p > 0.05$) or stability ($X^2_{(2)} = 3.25$, $p > 0.05$).

Discussion

The current investigation using a two-experiment approach, represents the first study to explore the effects of prophylactic knee bracing on ACL loading/ strains alongside lower extremity joint loading using musculoskeletal simulation in male and female football players. The debilitating nature of ACL injuries, the high rate of re-injury and the incidence of degenerative joint disease secondary to ACL injury, means that this study may provide important information necessary to inform future prevention strategies and insight into the cumulative biomechanical effects of prophylactic knee braces.

In relation to the ACL, experiment 1 showed that ACL loading and ACL strain were larger in the knee sleeve compared to no-sleeve. This observation opposes those of Sinclair et al.,³¹ and Sinclair et al.,³² who showed that prophylactic knee bracing attenuated knee joint soft tissue loading at the patellar tendon and ACL itself. Mechanically, aetiological analyses have shown that ACL injuries occur when the ligament itself experiences excessive tensile forces and strains¹². Given the increases in these parameters shown in experiment 1, it appears that prophylactic knee bracing akin to that examined in this study may increase the risk from the ligamentous parameters linked to the aetiology of injury. Therefore, during the sports specific movements examined in experiments 1 and 2, the findings do not support the utilization of prophylactic knee bracing for the attenuation ACL injuries.

419

420 At the tibiofemoral joint, experiment 1 indicated that lateral and total tibiofemoral compressive
421 loading was larger in the knee sleeve. As no-differences in medial tibiofemoral compartment
422 loading were found it can be concluded that differences in total tibiofemoral loading were
423 mediated through increases at the lateral tibiofemoral compartment. Whilst prophylactic knee
424 bracing has been shown to attenuate tibiofemoral loading quantified using the peak knee
425 adduction moment during a badminton lung30, there has yet to be an examination of the effects
426 of knee bracing on lateral tibiofemoral kinetics. Nonetheless, despite medial tibiofemoral
427 disorders being far more commonplace ⁴⁴, the aetiology of joint degenerative pathologies is
428 linked to excessive and habitual mechanical loading ⁴⁵. As such, experiment 1 indicates that
429 the knee sleeve may increase the risk from the biomechanical mechanisms linked to the
430 initiation of lateral tibiofemoral degeneration during the cut movement. Therefore, similar to
431 the conclusions in relation to the ACL, the findings do not support the utilization of
432 prophylactic knee bracing for the attenuation of knee joint injuries in male and female
433 footballers during 45°cut and single leg landing conditions.

434

435 At the hip joint, the findings from experiment 1 showed that both the shear and medial force
436 impulses were significantly larger in the knee sleeve condition compared to no-sleeve. This
437 observation supports the principles of the walking study shown by Toriyama et al., ⁴⁶, in that a
438 knee brace significantly attenuated hip joint kinetics of the ipsilateral side. This investigation
439 therefore highlights that knee sleeves affect joint mechanics in addition to those experienced
440 by the knee joint itself. Thus, it is recommended that future analyses concerning knee braces,
441 examine more than knee joint biomechanics in order to obtain a more cumulative representation
442 of their potential prophylactic effects. Regardless, as the aetiology of hip joint degeneration is

linked to the magnitude and frequency at which the applied mechanical loads are experienced⁴⁵, experiment 1 indicates that the knee sleeve may enhance the risk from the kinetic mechanisms linked to the initiation of hip joint degeneration.

Previous systematic analyses have proposed that prophylactic knee braces promote and facilitate safer landing biomechanics during functional athletic tasks by promoting an increased sensation of knee joint stability⁴⁷. However, the subjective and proprioceptive ratings from both experiments in the current investigation provide only partial support for this notion. Experiment 1 showed that the knee sleeve enhanced subjective knee joint stability yet in experiment 2 there were no perceptual alterations as a function of the sleeve, and neither investigation showed any improvement in knee joint proprioception. It is proposed that knee braces enhance knee joint stability and proprioception by stimulating sense receptors in the skin mediated through compression provided by the brace itself⁴⁷. However, the findings from experiment 1 do not appear to support this, as whilst improvements in perceived stability were shown, this did not translate into positive changes in knee biomechanics. It has been speculated previously that prophylactic sleeves do not provide sufficient compression to alter knee stability and proprioception sufficiently to mediate alterations in dynamic knee biomechanics²⁹. Therefore, although compression provided via the knee sleeve was not examined as part of the current investigation, an interesting avenue for future analyses may be to explore devices that provide different levels of compression in regards to their prophylactic efficacy.

A potential limitation to both experiments undertaken as part of the current investigation is the mechanism by which the musculoskeletal simulation-based analyses were completed. The CMC process, although an effective and robust tool for the quantification of muscle and soft

tissue kinetics utilized in previous analyses to simulate ACL mechanics³⁵, can be limited in its ability to quantify specific muscle coordination during dynamic tasks⁴⁸. Furthermore, that the ACL was not modelled with sex specificity in regard to its anatomy and scaling may serve as a drawback to this investigation. Although such an approach has yet to be developed within the simulation based musculoskeletal modelling literature; as the ACL contributes pointedly to knee mechanics, incorporation of sex-specific ligament modelling may improve the efficacy of musculoskeletal simulation analyses. Finally, that only relatively modest sample sizes were utilized in both experiments may have limited statistical power and alternate statistical observations may have arisen as a function of enhanced Bayes factors with the inclusion of additional participants⁴⁹.

Conclusion

The current investigation adds to the literature by exploring via a two-experiment investigation, the effects of prophylactic knee bracing on ACL loading/ strains and lower extremity joint biomechanics using a musculoskeletal simulation-based approach in male and female footballers. This study importantly showed in experiment 1 that ACL loading/ strain, lateral and total tibiofemoral compressive forces as well as hip joint shear and medial forces were greater in the knee sleeve condition and in experiment 2 that there were no statistical effects of the knee sleeve. Therefore, the findings from the current investigation suggest that the prophylactic knee sleeve examined in the current investigation does not appear to reduce the biomechanical parameters linked to the aetiology of knee pathologies in male/ female footballers.

References

1. Owøeye OB, VanderWey MJ Pike, I. Reducing injuries in soccer (football): an umbrella review of best evidence across the epidemiological framework for prevention. Sports Med Open 6: 1-8, 2020.
2. Stølen T, Chamari K, Castagna C Wisløff U. Physiology of soccer. Sports Med 35: 501-536, 2005.
3. Krstrup P, Dvorak J, Junge A, Bangsbo J (2010). Executive summary: The health and fitness benefits of regular participation in small-sided football games. Scand J Med Sci Sports, 20: 132-135, 2010.
4. Drawer S, Fuller CW (2002). Evaluating the level of injury in English professional football using a risk based assessment process. Br J Sports Med 36: 446-451.
5. Fuller CW. Assessing the return on investment of injury prevention procedures in professional football. Sports Med 49: 621-629, 2019.
6. Ekstrand J, Hägglund M, Waldén M. Injury incidence and injury patterns in professional football: the UEFA injury study. Br J Sports Med 45: 553-558, 2011.
7. Dönmez G, Korkusuz F, Özçakar L, Karanfil Y, Dursun E, Kudas S, Doral MN. Injuries among recreational football players: results of a prospective cohort study. Clin J Sport Med 28: 249-254, 2018.
8. Von Porat A, Roos EM, Roos H. High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. Ann Rheum Dis 63: 269-273, 2004.
9. Ellison AE, Berg EE (1985) Embryology, anatomy, and function of the anterior cruciate ligament. Orthop Clin N Am 16: 3–14.
10. Dargel J, Gotter M, Mader K, Pennig D, Koebke J, Schmidt-Wiethoff R (2007) Biomechanics of the anterior cruciate ligament and implications for surgical reconstruction. Strateg Trauma Limb Reconstr 2: 1–12

11. Waldén M, Krosshaug T, Børneboe J, Andersen TE, Faul O, Hägglund, M. Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: a systematic video analysis of 39 cases. *Br J Sports Med* 49: 1452-1460, 2015
12. Smith HC, Vacek P, Johnson RJ, Slauterbeck JR, Hashemi J, Shultz S, Beynnon BD. Risk factors for anterior cruciate ligament injury: a review of the literature—part 1: neuromuscular and anatomic risk. *Sport Health* 4: 69-78, 2012.
13. Shimokochi Y, Shultz SJ (2008) Mechanisms of noncontact anterior cruciate ligament injury. *J Athl Train* 43: 396–408.
14. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am Journal Sport Med* 32: 1002-1012, 2004.
15. Waldén M, Hägglund M, Magnusson H, Ekstrand J. ACL injuries in men's professional football: a 15-year prospective study on time trends and return-to-play rates reveals only 65% of players still play at the top level 3 years after ACL rupture. *Br J Sport Med*, 50: 744-750, 2016.
16. Gottlob CA, Baker CL, Pellissier JM, Colvin L. Cost effectiveness of anterior cruciate ligament reconstruction in young adults. *Clin Orthop Relat Res* 367: 272–282, 1999.
17. Kaeding CC, Pedroza AD, Reinke EK, Huston LJ, Spindler KP. Risk factors and predictors of subsequent ACL injury in either knee after ACL reconstruction: prospective analysis of 2488 primary ACL reconstructions from the MOON cohort. *Am J Sport Med* 43: 1583-1590, 2015.
18. Silvers HJ, Mandelbaum BR. Prevention of anterior cruciate ligament injury in the female athlete. *Br J Sport Med* 41: 52-59, 2007.

19. Di Stasi S, Myer GD, Hewett TE. Neuromuscular training to target deficits associated with second anterior cruciate ligament injury. *JOSPT* 43: 777-792, 2013.
20. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *Am J Sport Med* 44: 1861-1876, 2016.
21. Øiestad BE, Engebretsen L, Storheim K, Risberg MA. Knee osteoarthritis after anterior cruciate ligament injury a systematic review. *Am J Sports Med* 37:1434–1443, 2009.
22. Ajuied A, Wong F, Smith C, Norris M, Earnshaw P, Back D, Davies A. Anterior cruciate ligament injury and radiologic progression of knee osteoarthritis: a systematic review and meta-analysis. *Am Journal Sport Med* 42: 2242-2252, 2014.
23. Mather RC, Koenig L, Kocher MS, Dall TM, Gallo P, Scott DJ. Societal and economic impact of anterior cruciate ligament tears. *J Bone joint Surg* 95: 1751-1759, 2013.
24. Christino MA, Fleming BC, Machan JT, Shalvoy RM. Psychological factors associated with anterior cruciate ligament reconstruction recovery. *Orthop Journal Sport Med* 4: 2325967116638341, 2016.
25. Carey JL, Huffman GR, Parekh SG, Sennett BJ. Outcomes of anterior cruciate ligament injuries to running backs and wide receivers in the National Football League. *Am J Sport Med* 34: 1911-1917, 2006.
26. Roos H, Adalberth T, Dahlberg L, Lohmander LS. Osteoarthritis of the knee after injury to the anterior cruciate ligament or meniscus: the influence of time and age. *Osteoarthritis Cartilage*, 3, 261-267, 1995.
27. Sinclair J, Brooks D, Stainton P. Sex differences in ACL loading and strain during typical athletic movements: a musculoskeletal simulation analysis. *Europ J App Phys* 119: 713-721, 2019.

28. Sinclair JK, Vincent H, Richards JD. Effects of prophylactic knee bracing on knee joint kinetics and kinematics during netball specific movements. *Phys Ther Sport* 23: 93-98, 2017.
29. Sinclair J, Taylor PJ, Foxcroft H. Effects of prophylactic knee bracing on knee joint kinetics and kinematics during single-and double-limb post-catch deceleration strategies in university netballers. *Sport Sci Health* 15: 215-222, 2019.
30. Valdecabres R, de Benito AM, Littler G, Richards J. An exploration of the effect of proprioceptive knee bracing on biomechanics during a badminton lunge to the net, and the implications to injury mechanisms. *PeerJ* 6: e6033, 2018.
31. Sinclair J, Richards JD, Taylor PJ. Effects of prophylactic knee bracing on patellar tendon loading parameters during functional sports tasks in recreational athletes. *Sport Sci Health* 14; 151-160, 2018.
32. Sinclair J, Taylor PJ. Effects of a Prophylactic knee sleeve on anterior cruciate ligament loading during sport-specific movements. *J Sport Rehabil*, 28; 1-7, 2019.
33. Herzog W, Longino D, Clark A (2003) The role of muscles in joint adaptation and degeneration. *Langenbecks Arch Surg* 388: 305–315.
34. Herzog W, Clark A, Wu J (2003) Resultant and local loading in models of joint disease. *Arthritis Care Res* 49: 239–247.
35. Kar J, Quesada PM. A musculoskeletal modeling approach for estimating anterior cruciate ligament strains and knee anterior–posterior shear forces in stop-jumps performed by young recreational female athletes. *Ann Biomed Eng* 41: 338–348, 2013.
36. Delp SL, Anderson FC, Arnold AS, Loan P, Habib A, John CT, Thelen DG. OpenSim: open-source software to create and analyze dynamic simulations of movement. *IEEE Trans Biomed Eng* 54; 1940-1950, 2007.

37. Sinclair J, Taylor PJ, Currigan G, Hobbs SJ. The test-retest reliability of three different hip joint centre location techniques. *Movement & Sport Sciences* 83: 31-39, 2014.
38. Sinclair J, Hebron J, Taylor PJ. The test-retest reliability of knee joint center location techniques. *J App Biomech* 31: 117-121., 2015.
39. Graydon RW, Fewtrell DJ, Atkins S, Sinclair JK. The test-retest reliability of different ankle joint center location techniques. *FAOJ* 1: 15-18, 2015.
40. Xu H, Bloswick D, Merryweather A. An improved OpenSim gait model with multiple degrees of freedom knee joint and knee ligaments. *Comput Methods Biomech Biomed Eng* 18: 1217-1224., 2015.
41. Barrios, J., & Willson, J. (2017). Minimum detectable change in medial tibiofemoral contact force parameters: derivation and application to a load-altering intervention. *Journal of applied biomechanics*, 33(2), 171-175.
42. Jeffreys H. *Theory of probability* (3rd Ed.) 1961. Oxford, UK: Oxford University Press.
43. Laughlin WA, Weinhandl JT, Kernozek TW, Cobb SC, Keenan KG, O'Connor KM. The effects of single-leg landing technique on ACL loading. *Journal Biomech* 44: 1845-1851, 2011.
44. Jones RK, Chapman GJ, Forsythe L, Parkes MJ, Felson DT. The relationship between reductions in knee loading and immediate pain response whilst wearing lateral wedged insoles in knee osteoarthritis. *J Orthop Res* 32: 1147-1154, 2014.
45. Griffin TM, Guilak F. The role of mechanical loading in the onset and progression of osteoarthritis. *Ex Sport Sci Rev* 33: 195-200, 2005.
46. Toriyama M, Deie M, Shimada N, Otani T, Shidahara H, Maejima H, Ochi M. Effects of unloading bracing on knee and hip joints for patients with medial compartment knee osteoarthritis. *Clinical Biomech* 26: 497-503, 2011.

47. Herrington L, Simmonds C, Hatcher J. The effect of a neoprene sleeve on knee joint position sense. Res Sport Med 13: 37–46, 2005.

48. Zajac FE, Neptune RR, Kautz SA. Biomechanics and muscle coordination of human walking: part I: introduction to concepts, power transfer, dynamics and simulations. Gait Posture 16: 215–232, 2002.

49. De Santis, F. Alternative Bayes factors: Sample size determination and discriminatory power assessment. Test 16: 504-522, 2007.

Tables

Table 1: ACL and joint forces (Means $\pm$ standard deviations) for each knee sleeve condition – from experiment 1.

	Knee sleeve		No-sleeve	
	Mean	SD	Mean	SD
Peak ACL force (BW)	1.19	0.36	0.94	0.33
Peak ACL strain (%)	13.57	4.84	10.26	2.38
Peak ACL strain (%/s)	75.37	10.96	80.87	12.39
Peak hip compressive force (BW)	9.97	1.84	9.80	1.74
Hip compressive impulse (BW·ms)	1652.58	433.36	1708.26	452.87
Peak hip shear force (BW)	2.74	1.35	2.49	1.21
Hip shear impulse (BW·ms)	194.20	306.42	92.70	286.98
Hip peak medio-lateral force (BW)	4.93	1.15	5.85	1.10
Hip medio-lateral impulse (BW·ms)	702.52	301.03	830.84	310.57
Peak patellofemoral compressive force (BW)	10.08	2.45	10.17	3.00
Patellofemoral compressive impulse (BW·ms)	1350.34	465.84	1414.64	531.04
Peak medial tibiofemoral condyle compressive force (BW)	7.22	1.50	7.11	1.51
Medial tibiofemoral condyle compressive impulse (BW·ms)	1052.14	284.94	1021.79	301.41
Peak medial tibiofemoral condyle shear force (BW)	3.84	1.03	4.30	0.76
Medial tibiofemoral condyle shear impulse (BW·ms)	532.59	153.16	641.38	149.64
Peak medial tibiofemoral medio-lateral force (BW)	2.22	1.41	1.96	1.03
Peak medial tibiofemoral medio-lateral impulse (BW·ms)	306.96	196.94	265.22	195.17
Peak lateral tibiofemoral condyle compressive force (BW)	4.70	0.95	4.20	1.14
Lateral tibiofemoral condyle compressive impulse (BW·ms)	698.05	273.28	660.11	285.97
Peak lateral tibiofemoral condyle shear force (BW)	2.30	0.71	2.41	0.90
Lateral tibiofemoral condyle shear impulse (BW·ms)	316.40	149.65	334.28	163.53
Peak lateral tibiofemoral medio-lateral force (BW)	1.88	0.83	1.68	0.50
Peak lateral tibiofemoral medio-lateral impulse (BW·ms)	265.43	134.46	231.05	94.07
Peak total tibiofemoral compressive force (BW)	11.73	2.34	11.08	2.49

Total tibiofemoral compressive impulse (BW·ms)	1750.18	534.36	1681.90	569.46
Peak total tibiofemoral shear force (BW)	5.87	1.32	6.45	1.15
Total tibiofemoral shear impulse (BW·ms)	849.00	209.43	975.66	268.93
Peak total tibiofemoral medio-lateral force (BW)	3.79	2.27	3.31	1.48
Peak total tibiofemoral medio-lateral impulse (BW·ms)	572.39	318.22	496.27	268.97
Peak ankle compressive force (BW)	10.36	1.48	10.08	2.13
Ankle compressive impulse (BW·ms)	1525.02	387.94	1453.99	408.65
Peak ankle shear force (BW)	3.14	0.91	3.20	1.24
Ankle shear impulse (BW·ms)	191.72	237.15	100.94	255.53
Peak ankle medio-lateral force (BW)	3.96	3.96	3.94	3.94
Ankle medio-lateral impulse (BW·ms)	550.48	245.11	510.37	188.78

Notes: bold text = statistical difference between knee-sleeve and no-sleeve conditions (BF >3.00).

Table 2: Knee joint kinematics (Means ± standard deviations) for each knee brace condition – from experiment 1.

	Knee sleeve		No-sleeve	
	Mean	SD	Mean	SD
Peak knee flexion (°)	60.94	11.63	60.08	9.52
Peak knee abduction (°)	11.44	5.99	13.33	8.81
Peak knee internal rotation (°)	10.04	6.48	6.06	7.86
Peak knee flexion velocity (°/s)	505.39	70.22	464.80	113.63
Peak knee abduction velocity (°/s)	205.60	127.17	161.93	69.48
Peak knee internal rotation velocity (°/s)	288.25	150.05	308.87	108.13
Proprioception angular error (°)	3.93	1.93	4.23	1.88

Table 3: Muscle forces (Means ± standard deviations) for each knee sleeve condition – from experiment 1.

	Knee sleeve		No-sleeve	
	Mean	SD	Mean	SD
Peak biceps femoris long head force (BW)	0.49	0.31	0.46	0.33
Biceps femoris long head impulse (BW·ms)	39.60	48.66	31.17	31.03
Peak biceps femoris short-head force (BW)	0.79	0.29	0.83	0.26
Biceps femoris short head impulse (BW·ms)	60.11	36.24	59.85	28.25
Peak gracilis force (BW)	0.14	0.06	0.21	0.10
Gracilis impulse (BW·ms)	7.61	5.15	10.27	5.47
Peak lateral gastrocnemius force (BW)	1.11	0.25	1.03	0.36
Lateral gastrocnemius impulse (BW·ms)	81.85	29.55	75.65	34.28
Peak medial gastrocnemius force (BW)	2.18	0.62	2.41	0.57
Medial gastrocnemius impulse (BW·ms)	166.00	65.81	172.83	57.86
Peak rectus femoris force (BW)	2.83	0.65	2.87	0.57
Rectus femoris impulse (BW·ms)	358.71	165.51	381.55	178.20

Peak semimembranosus force (BW)	0.84	0.46	0.80	0.41
Semimembranosus impulse (BW·ms)	59.06	33.27	55.53	31.33
Peak semitendinosus force (BW)	0.27	0.10	0.27	0.11
Semitendinosus impulse (BW·ms)	15.34	7.51	15.06	7.36
Peak total hamstring force (BW)	1.80	0.73	1.61	0.61
Total hamstring impulse (BW·ms)	174.11	89.74	161.61	75.78
Peak total quadriceps force (BW)	9.80	1.92	9.39	2.21
Total quadriceps impulse (BW·ms)	1412.64	397.21	1417.13	437.73
Peak vastus intermedius force (BW)	2.61	0.48	2.46	0.70
Vastus intermedius impulse (BW·ms)	309.22	75.38	304.77	95.09
Peak vastus lateralis force (BW)	3.97	0.68	3.77	0.97
Vastus lateralis impulse (BW·ms)	457.30	121.75	450.42	149.08
Peak vastus medialis force (BW)	2.43	0.49	2.27	0.68
Peak vastus medialis impulse (BW·ms)	287.41	72.86	280.39	88.58

Notes: bold text = statistical difference between knee-sleeve and no-sleeve conditions (BF >3.00).

Table 4: ACL and joint forces (Means ± standard deviations) for each knee sleeve condition – from experiment 2.

	Knee sleeve		No-sleeve	
	Mean	SD	Mean	SD
Peak ACL force (BW)	0.97	0.18	0.92	0.11
Peak ACL strain (%)	12.83	3.06	11.71	1.35
Peak ACL strain (%/s)	105.94	11.57	106.67	19.57
Peak hip compressive force (BW)	9.82	2.00	10.16	1.55
Hip compressive impulse (BW·ms)	1450.31	295.85	1521.78	273.71
Peak hip shear force (BW)	2.19	0.48	2.52	0.69
Hip shear impulse (BW·ms)	302.29	118.70	368.95	153.17
Hip peak medio-lateral force (BW)	1.39	0.66	1.50	0.75
Hip medio-lateral impulse (BW·ms)	178.76	109.51	194.07	79.30
Peak patellofemoral compressive force (BW)	8.13	1.24	8.01	1.98
Patellofemoral compressive impulse (BW·ms)	1309.86	428.92	1337.48	568.47
Peak medial tibiofemoral condyle compressive force (BW)	6.83	1.61	6.80	1.04
Medial tibiofemoral condyle compressive impulse (BW·ms)	1042.57	221.16	1096.50	355.52
Peak medial tibiofemoral condyle shear force (BW)	2.69	0.26	2.70	0.52
Medial tibiofemoral condyle shear impulse (BW·ms)	424.84	131.27	409.98	140.09
Peak medial tibiofemoral medio-lateral force (BW)	0.92	0.30	0.82	0.27
Peak medial tibiofemoral medio-lateral impulse (BW·ms)	136.67	51.50	132.54	72.57
Peak lateral tibiofemoral condyle compressive force (BW)	5.22	0.95	4.65	0.56
Lateral tibiofemoral condyle compressive impulse (BW·ms)	618.42	122.87	639.73	153.60
Peak lateral tibiofemoral condyle shear force (BW)	1.84	0.38	1.82	0.46
Lateral tibiofemoral condyle shear impulse (BW·ms)	274.89	96.87	270.80	118.40
Peak lateral tibiofemoral medio-lateral force (BW)	0.32	0.15	0.30	0.08
Peak lateral tibiofemoral medio-lateral impulse (BW·ms)	27.63	19.11	25.58	17.72

Peak total tibiofemoral compressive force (BW)	11.27	1.97	10.63	0.97
Total tibiofemoral compressive impulse (BW·ms)	1660.99	312.75	1736.22	496.97
Peak total tibiofemoral shear force (BW)	4.42	0.60	4.37	0.92
Total tibiofemoral shear impulse (BW·ms)	699.73	222.50	680.78	255.84
Peak total tibiofemoral medio-lateral force (BW)	1.22	0.43	1.06	0.33
Peak total tibiofemoral medio-lateral impulse (BW·ms)	164.30	65.60	158.13	83.70
Peak ankle compressive force (BW)	8.69	1.29	8.97	1.48
Ankle compressive impulse (BW·ms)	1393.27	219.68	1442.64	333.20
Peak ankle shear force (BW)	2.33	0.57	1.99	1.29
Ankle shear impulse (BW·ms)	270.75	164.04	226.61	209.43
Peak ankle medio-lateral force (BW)	0.68	0.34	0.77	0.63
Ankle medio-lateral impulse (BW·ms)	62.85	53.41	67.67	54.34

Table 5: Knee joint kinematics (Means $\pm$ standard deviations) for each knee brace condition – from experiment 2.

	Knee sleeve		No-sleeve	
	Mean	SD	Mean	SD
Peak knee flexion (°)	65.71	7.89	66.80	8.46
Peak knee abduction (°)	4.93	3.62	3.54	3.95
Peak knee internal rotation (°)	1.66	8.46	1.78	4.35
Peak knee flexion velocity (°/s)	639.08	17.85	641.84	52.57
Peak knee abduction velocity (°/s)	102.89	41.47	159.01	50.95
Peak knee external rotation velocity (°/s)	206.35	102.86	180.05	71.63
Proprioception angular error (°)	4.13	2.39	4.42	2.15

Table 6: Muscle forces (Means $\pm$ standard deviations) for each knee sleeve condition – from experiment 2.

	Knee sleeve		No-sleeve	
	Mean	SD	Mean	SD
Peak biceps femoris long head force (BW)	0.37	0.16	0.53	0.21
Biceps femoris long head impulse (BW·ms)	39.07	33.30	44.42	19.98
Peak biceps femoris short-head force (BW)	0.37	0.19	0.55	0.27
Biceps femoris short head impulse (BW·ms)	19.88	8.22	33.72	24.87
Peak gracilis force (BW)	0.06	0.03	0.06	0.03
Gracilis impulse (BW·ms)	3.22	1.38	3.62	2.04
Peak lateral gastrocnemius force (BW)	0.50	0.16	0.73	0.31
Lateral gastrocnemius impulse (BW·ms)	44.59	16.82	62.47	32.80
Peak medial gastrocnemius force (BW)	1.20	0.34	1.69	0.66
Medial gastrocnemius impulse (BW·ms)	93.97	55.19	114.90	46.88
Peak rectus femoris force (BW)	1.96	0.33	1.90	0.36
Rectus femoris impulse (BW·ms)	161.77	40.99	176.52	36.50
Peak semimembranosus force (BW)	0.45	0.19	0.71	0.36
Semimembranosus impulse (BW·ms)	35.81	23.82	50.87	30.94

Peak semitendinosus force (BW)	0.18	0.07	0.18	0.06
Semitendinosus impulse (BW·ms)	10.04	4.61	13.89	6.55
Peak total hamstring force (BW)	1.21	0.41	1.68	0.48
Total hamstring impulse (BW·ms)	104.80	64.93	142.90	52.45
Peak total quadriceps force (BW)	7.95	1.25	7.42	1.40
Total quadriceps impulse (BW·ms)	1284.33	360.81	1285.00	532.72
Peak vastus intermedius force (BW)	2.04	0.36	1.85	0.49
Vastus intermedius impulse (BW·ms)	319.08	100.44	315.40	144.75
Peak vastus lateralis force (BW)	3.15	0.37	2.96	0.76
Vastus lateralis impulse (BW·ms)	513.36	159.53	502.71	227.52
Peak vastus medialis force (BW)	1.85	0.35	1.76	0.46
Peak vastus medialis impulse (BW·ms)	290.12	95.97	290.38	135.55

640

641 **Figure labels**

642 **Figure 1: Experimental knee sleeve.**

643 **Figure 2: Experimental laboratory set-up with motion capture system cameras numbered**
644 **according to the laboratory system and force platform (FP). Approach (A) and cut (C)**
645 **directions are labelled with arrows showing participants direction of travel as part of the 45°**
646 **cut movement.**

647 **Figure 3: a. Experimental marker locations and b. trunk, pelvis, thigh, shank and foot segments,**
648 **with segment co-ordinate system axes (R = right & L = left), (TR = trunk, P = pelvis, T = thigh,**
649 **S = shank & F = foot), (X = sagittal, Y = coronal & Z = transverse planes).**

650 **Figure 4: Weight-bearing knee joint position sense test from a. frontal and b. sagittal**
651 **viewpoints.**

652 **Figure 5: a. Experimental Opensim model in full and b. with only the ACL bundles visible.**