

1 The effect of sand on knee load during a single leg jump task: implications for injury

2 prevention and rehabilitation programmes.

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ABSTRACT

The purpose of the study was to determine potential differences in landing strategies and subsequent joint loads at the knee (knee abduction moment, anterior-posterior tibial translation and total knee shear force) when jumping onto sand and firm ground from both a level surface and a 30_cm height. Firm ground would act as the control for the study.

17 subjects (age: 23.6 ± 3.7 years; body mass: 67.7 ± 10.3 kg; height: 168.5 ± 7.4 cm) performed 3 single leg jumps on their dominant leg for each of the four conditions tested (ground level, sand level, ground height and sand height). A repeated measures design investigated the effect of sand on knee abduction moment, anterior-posteriorAP tibial translation and total knee shear force. Data was analyzed using magnitude-based inferences and presented as percentage change with 90_% confidence limits.

Results indicated that sand had a clear beneficial effect on knee abduction moment, which was possibly moderate during a drop jump (30_cm) and possibly small from a level jump. Sand also had a possibly moderate beneficial effect on anterior-posterior tibial translation from a level jump. The effect of sand on total knee shear force was unclear.

These results suggest that sand may provide a safer alternative to firm ground when performing jump tasks commonly used in ACL and PFJ injury prevention and rehabilitation programmes. Sand may also allow for an accelerated rehabilitation program, as jumping activities could potentially be implemented more safely at an earlier stage in the process.

Key Words: anterior cruciate ligament, patello-femoral joint, knee abduction moment, anterior-posterior tibial translation.

INTRODUCTION

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Over a 10-year study period, analysing 26 different sports, and 17397 patients, Majewski et al. (35) documented 19530 sporting injuries. 7769 related to the knee joint with over 20% of these involving an anterior cruciate ligament (ACL) lesion. ACL injuries were most commonly associated with handball and volleyball activities. A high incidence of patellofemoral joint (PFJ) injuries has also been reported (9). As with ACL lesions, these can result in significant time lost from sport and future risk of osteoarthritis (44). Establishing an effective intervention to help prevent these injuries whilst at the same time enabling an acceleration of the rehabilitation process would be desirable.

To establish an intervention, it is essential to have a good understanding of the mechanisms and risk factors for PFJ and ACL injuries. The majority of these injuries are the result of a non-contact mechanism, with jump landing being the most frequently cited cause (1,7,22). Landing from a jump places high forces and moments on the knee joint. A component of knee joint force that can increase strain on the ACL is proximal tibia anterior shear force (50), given that it represents the most direct loading mechanism ~~of the ACL~~ (49). To estimate this loading of the ACL, anterior-posterior (AP) tibial translation is often used as an indirect measure (29). Another load mechanism commonly associated with the development of both PFJ and ACL injuries is knee valgus (8,23), with knee abduction moment (KAM) frequently recorded as a significant predictor of injury (42).

Interventions that can help the athlete to cope with these joint loads, specifically in jumping exercises should be integral to injury prevention and rehabilitation programmes for both ACL

57 and PFJ injuries. To date, these have been carried out on firm surfaces, aiming to improve
58 neuromuscular control of the lower limb (15). However, Binnie et al. (5) suggested that sand,
59 as a less stable surface may be a viable option for such interventions. Most notably, its unique
60 characteristics are thought to reduce impact forces through the body (2,6). Previous studies
61 have also demonstrated a reduced rate and extent of musculoskeletal loading (28,38), alongside
62 muscle activation strategies which provide more joint stability (47) when training on sand
63 compared to firm surfaces. Furthermore, physiological (improved lactate threshold, aerobic
64 capacity) and performance benefits (improved speed, agility, squat jump) on sand have been
65 well documented (3,4,5,20,28,46) in both running and plyometric activities, and team sports.
66 Moreover, evidence of improvements transferring to future firm ground performance in both
67 running and agility tasks has been reported (20, 57). Although, the growing support for the use
68 of sand in training interventions is evident the effects on common knee joint loads associated
69 with ACL and PFJ injuries is unknown, and could have significant implications for the safety
70 of both rehabilitation and injury prevention interventions.

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72 To date, no study to our knowledge has examined the effects on knee joint loads, using a less
73 stable sand surface compared to a firm surface during a jumping task. The purpose of this study
74 was to determine whether differences were apparent in landing strategies and subsequent joint
75 loads at the knee (KAM, AP tibial translation and total knee shear force) when hopping onto
76 sand and firm ground from both a level surface and a 30 cm height. The functional test chosen
77 for the jump task was a single leg hop (SLH) due to its use in a clinical setting to assess knee
78 function (48).

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METHODS

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Experimental Approach to the Problem

This study was designed to compare the effect of sand and firm ground surfaces on knee load during a single leg jumping task. To achieve this, subjects were required to perform three single leg jumps for each of the four different test conditions (A, B, C and D) on their dominant leg in a repeated measures design (Fig. 1, Fig. 2). Each individual participant decided leg dominance by asking which leg he or she took off with during a vertical jump. The four conditions were performed in a randomised order using a computer-generated system. This allowed the effects of the order of jumps to be counterbalanced preventing each condition from adversely influencing outcome measures. Each trial was separated by three minutes to eliminate carryover effects. KAM, AP tibial translation and total knee shear force were measured during each single leg jump. This arrangement allowed for a comparison of sand to firm ground on knee load.

Figure 1. An illustration of the four test conditions (ground level, sand level, ground height, sand height). Picture with depicted marker set, used with permission from Vicon Motion Systems UK. (16)

Insert Fig. 1 here

Figure 2. An illustration of the experimental set up.

Insert Fig. 2 here

Subjects

Seventeen University students (14 females, 3 males; age: 23.6 ± 3.7 years; body mass: 67.7 ± 10.3 kg; height: 168.5 ± 7.4 cm) who participated in more than 3 hours of sporting activity per week were recruited for the study. All subjects had no history of ACL injury or other knee pathology, significant lower limb pathology, lower limb fracture or surgery and had been injury

110 free for 3 months prior to data collection. All subjects were informed of the benefits and risks
111 of the investigation prior to signing an institutionally approved informed consent document to
112 participate in the study. The study received ethical approval by Teesside University's ethics
113 committee (Ethics Number: SSSBLREC035), in accordance with the Declaration of Helsinki.

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115 Procedures

116 Initial pilot work was conducted to assess the Az plane of the force plates to determine
117 whether centre of pressure (COP) measures would remain accurate with the sand covering so
118 that inverse dynamics could be performed. We found that comparisons between the data with
119 and without the sand covering were a nearly perfect relationship ($p = 0.97$ and $p = 0.99$; for
120 static and dynamic trials respectively).

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122 Participants attended the laboratory on two occasions; firstly, for a familiarisation session and
123 secondly for data collection. The familiarisation session allowed the subjects 3 to 5 practice
124 trials of each of the 4 different hops on each surface, to orient themselves to these different
125 conditions. The four conditions were hops on a level surface onto the laboratory floor (ground
126 level), a level surface onto sand (sand level), from a 30 cm height onto the laboratory floor
127 (ground height) and from a 30 cm height onto sand (sand height). The four conditions and
128 experimental set up are shown in Figures 1 (A-D) and 2. The study took place within a
129 laboratory setting at Teesside University at the same time of day (9-11am for each participant)
130 to limit diurnal differences. Before testing, subjects were instructed to fast overnight and refrain
131 from consuming caffeine for the previous 24 hours. All participants also had to refrain from
132 strenuous muscular exercise for 48 hours prior to testing.

133

134 Prior to testing a standardised warm-up programme was performed which included 10 minutes
135 on a stationary bike, stretching of the gluteus maximus, hamstrings, quadriceps and
136 gastrocnemius (21, 55). Subjects were fitted with a heart rate monitor and asked to cycle at 60
137 % of their age predicted heart rate max. All muscle groups were stretched statically three times
138 for a 30-second duration, with subjects instructed to stretch to the ‘point just before pain’. The
139 differences in kinematic and kinetic landing strategies of single leg hopping were investigated
140 using the four conditions. Kinematic variables were collected using a commercially available
141 six-camera motion capture system (Vicon MX13 and Vicon Nexus 1.7, Vicon Motion Systems,
142 UK). The six-camera system is a passive video-based 3D motion capture system, which was
143 calibrated prior to every session, following manufacturers’ guidelines, to ensure image error
144 was below 0.18 mm (34). Cameras for the six-camera system were set at a height of 1.9 m and
145 a sampling frequency of 100 Hz. Throughout testing participants were required to wear tight
146 fitting Velcro kinematic suits (Vicon Motion Systems, UK) to allow for placement of retro-
147 reflective markers in accordance with the full-body plug-in-gait marker set (Vicon Motion
148 Systems, UK), as previously used by Gehring et al. (19) when evaluating knee joint kinematics
149 and kinetics during a landing task. This included markers placed on the head, arms, wrists,
150 hands, trunk, pelvis, legs and feet, and has been outlined in detail previously (10,45) (Fig. 3).
151 Marker trajectories were filtered using a Woltring Filter with a low-pass cut-off frequency of
152 10 Hz and stop-band frequency of 30 Hz. Kinematic and kinetic data were both processed using
153 the Vicon’s validated Plug-in Gait full body modelling software. Kinetic variables were
154 collected using two force platforms (Kistler 9281CA Force Platforms, Kistler Instrument
155 Corp., Switzerland) that were placed in the floor space of the laboratory and were collected
156 concurrently with the motion capture system. The sand (particle size 0.02-0.2 mm) (Building
157 Sand, Wickes, UK) was placed in a purpose-built pit with deformable sides and base, to allow
158 lateral displacement of the sand, and the transmission of forces onto and from the force plate.

159 The sand was at a depth of 10 cm and placed directly on top of the force platforms in the
160 laboratory (Fig.1, Fig. 2). When hopping onto the sand pit from the same level as the top of
161 sand participants stood on a 10 cm plyometric box (Foam Plyometric Box, Perform Better Ltd.,
162 UK) (Fig. 1 B). When hopping onto the sand from a 30_cm height, a 40_cm box was used to
163 account for the change in height (Fig. 1 D).

164

165 ***Figure 3. The Marker placement of the Vicon Plug in Gait Model as presented from the***
166 ***manufacturers guidelines (Vicon Motion Systems, Oxford, UK).***

167

168 ***Insert Fig. 3 here***

169

170 The SLH test has high reliability (ICC: $r = 0.97$, 95% CI; $0.9 - 0.99$) (31) and also places high
171 demand on the lower extremity to absorb ground reaction forces (13). Participants were
172 instructed to stand on one leg and to position toes as close as possible to a predetermined floor
173 marker (Fig. 2). The subject began the hop standing on one leg, keeping the hands static on the
174 hips throughout the jump. Subjects were instructed to hop forward onto either the floor or sand
175 during a level jump or hop down onto the floor or sandpit from a 30_cm height. A pre-
176 determined floor marker 30_cm from the subjects starting position was used to standardise
177 landing position (Fig. 2). A controlled landing was instructed for all test conditions by asking
178 the subjects to land with a flat foot and hold the position on landing (43). Each condition was
179 completed three times on the dominant leg. Trials in which the foot did not land completely on
180 the force platform were discarded and subsequently repeated. Following each landing on the
181 sand surface the sand was raked prior to the next jump to ensure an evenly distributed surface
182 and a consistent 10_cm depth. During each condition, KAM, AP tibial translation and knee
183 shear force were calculated throughout the complete movement. Data was exported, using a
184 pipeline provided by the software manufacturers (Vicon Motion Systems, UK), into Microsoft

185 Excel so that data could be edited ready for analysis. Data from the initial 50 milliseconds
186 immediately after contact with the force platforms was used for analysis as this time period
187 provides the greatest risk of injury (33).

188

189 Statistical Analyses

190 Raw data, absolute and relative to body mass (kg), are presented as the mean \pm SD. Using a
191 custom-made spreadsheet (25) all data was logged transformed and then back transformed to
192 obtain the percentage difference, with uncertainty of the estimates expressed as 90_%
193 confidence limits between conditions for each outcome measure. Threshold values of 0.2, 0.6
194 and 1.2 represented small, moderate and large effects, respectively, with magnitude-based
195 inferences subsequently applied (26). The probability of a substantial true population
196 difference was assigned the following descriptors: <0.5_% most unlikely; 0.5-5_%, very
197 unlikely; 5-25_% unlikely; 25-75_%, possibly; 75-95_%, likely; 95-99.5_%, very likely; >99.5
198 %, most likely (26). Clear mechanistic effects (<5_% chance of the CL overlapping both
199 substantially positive and negative thresholds) were qualified as per Hopkins et al. (26).

200

201

RESULTS

202 Descriptive statistics for the dependent variables are displayed in Table 1. Differences in
203 dependent variables between surface conditions at two different heights are displayed in Table
204 2. Compared to landing on a firm surface from a 30_cm height, KAM was lower when landing
205 on a sand surface. AP tibial translation was also lower on a sand surface, during a level jump.
206 Effect sizes for these two conditions were moderate. There was no difference in knee shear
207 force when landing on either surface at either height.

208

209

210 ***Table 1: Raw data, presented as both absolute and relative to body mass (kg), (Mean ± SD)***
211 ***of the four conditions for the three outcome measures examined in this study***

212

213 ***Insert Table 1 here***

214

215 ***Table 2: Between condition differences for relative knee shear force, relative knee abduction***
216 ***moment and absolute anterior-posterior tibia translation***

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218 ***Insert Table 2 here***

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DISCUSSION

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224 The purpose of this study was to determine whether differences were apparent in landing

225 strategies and knee joint loads (KAM, AP tibial translation and total knee shear force) when

226 hopping onto sand and firm ground from both a level surface and a 30_cm height. As these

227 joint loads have been established as significant risk factors for ACL and PFJ injury, the study

228 would help provide some initial data as to whether the use of sand in injury prevention and

229 rehabilitation programmesprogrammes may reduce these loads, and subsequent injury risk

230 compared to a firm surface. The main findings of this study were that KAM was lower when

231 undertaking a drop jump (30_cm) onto a sand surface compared to a firm one. AP tibial

232 translation was also lower on a sand surface compared to a firm one, during a level jump. The

233 magnitude of these effects was moderate and it is possible that these differences hold true for

234 the population. These findings provide some initial support for the use of a less stable sand

235 surface to reduce knee joint loads commonly associated with ACL and PFJ injury during both

236 horizontal and vertical jumping tasks.

237

238 Most ACL and PFJ injuries occur during non-contact activities such as jumping and landing

239 (1,7,22) on different surfaces, although little data exists regarding knee joint loads when

240 training on these surfaces. Hence, there is no data to directly compare the effects of sand on

241 knee joint loads. Furthermore, the value of -KAM and amount of AP tibial translation on

242 landing which becomes significant in terms of creating the injury risk is also unknown.
243 Previous KAM values of 18.4 ± 15.6 N.m during the landing of a 30 cm drop jump in uninjured
244 female athletes participating in high-risk sports for ACL injury (soccer, basketball, volleyball)
245 have been reported (23). Our results, show similar values of 17.3 ± 5.9 N.m for a firm surface
246 with a reduction to 14.8 ± 5.2 N.m when landing on a sand surface from a 30 cm height.
247 Increased KAM during landing has been significantly correlated with an increase in lower
248 extremity valgus alignment (23,32,42). The link between increased knee valgus and resultant
249 ACL strain and PFJ injuries has been widely documented through both cadaver and in vivo
250 research (7,18,24,33,36). It is therefore likely that the reduction in KAM observed when
251 landing on the sand surface from a 30 cm height would lead to a reduction in valgus loading
252 compared to a firm surface, and a subsequent decrease in ACL and PFJ injury risk. Given that
253 knee valgus on landing is also a common technique flaw amongst athletes, and can be reliably
254 used to screen landing performance (37), the reduction in KAM provides some early support
255 for considering the use of a less stable sand surface in both rehabilitation and prevention
256 programmes, for individuals who are considered to be at a heightened risk.

257

258 Regarding AP tibial translation, previous average values ranging from 8.5 mm to 13 mm for
259 uninjured ACLs have been reported using cadaveric specimens, and on participants with and
260 without anaesthesia (14,30,39). Our results, although in more dynamic conditions, showed
261 similar values ranging from 11.8 ± 4.0 mm to 14.4 ± 5.6 mm across the four conditions
262 measured, with a reduction from 12.6 ± 3.7 mm to 11.8 ± 4.0 mm on sand during a horizontal
263 jump. Landing on a sand surface therefore during jumping exercises would appear to have two
264 major benefits. Reduced AP tibial translation is evident on horizontal jump landings and
265 reduced KAM is evident when landing from a drop jump.

266

267 Although KAM and AP tibial translation data is limited, a number of other studies have
268 demonstrated biomechanical data on changes occurring resulting from landing on various
269 surfaces. Moritz and Farley (41) demonstrated that humans alter kinematics and/or muscle
270 activation 3-76_{ms} before landing, when expecting a surface stiffness change. Subjects landed
271 with more knee flexion and increased their muscle activation 24-76% during the 50_{ms} before
272 landing on the expected hard surface compared to a consistently soft surface. Leg stiffness was
273 also 47% lower on the expected hard surface than on the consistently soft surface immediately
274 after touchdown. However, for unexpected surface changes, they demonstrated that hoppers
275 use passive mechanics to change leg stiffness, compensate for the new surface soon after
276 landing and before any changes in neural activity occur. These mechanical reactions to
277 landing, caused by intrinsic muscle properties termed ‘preflexes’, and passive dynamics of the
278 body’s linked segments, are thought to contribute to adjustments for new surfaces more rapidly
279 than reflexes (41). This suggests that neural feedback is not a prerequisite for a change in leg
280 stiffness, and was further supported by the findings of Van der Krogt et al (54) for both
281 unexpected hard and unexpected soft surfaces. Although leg stiffness and neural activity were
282 not directly measured in our study, the subjects were not blinded to the surface for each hop.
283 This increases the likelihood that neural anticipation rather than passive mechanics played a
284 significant role in subjects adapting their landing strategy for the expected surface change,
285 when hopping onto both the firm and less stable sand surface. It is possible that these adaptations
286 on the firm and sand surface may account for some of the differences in both KAM and AP
287 tibial translation reported.

288

289 With unexpected perturbations, previous work by Daley et al. (12) demonstrated a proximo-
290 distal gradient in limb neuromuscular performance and motor control. They demonstrated that
291 the proximal muscles at the hip and knee joints of a helmeted guinea fowl were controlled

292 primarily in a feedforward manner and exhibited load-insensitive mechanical performance at
293 ground contact. However, the distal muscles at the ankle and tarsometatarso-phalangeal (TMP)
294 joints were highly load-sensitive, due to intrinsic mechanical effects and rapid, higher gain
295 proprioceptive feedback. The hip also maintained the same mechanical role regardless of limb
296 loading, whereas the ankle and TMP switched between spring-like function with an increased
297 amount of knee flexion at ground contact and damping function as the knee became more
298 extended at ground contact. Whether or not this proximo-distal gradient in limb neuromuscular
299 performance and motor control would be evident with an expected perturbation in humans,
300 such as a jump onto an anticipated less stable sand surface is unclear, and warrants further
301 investigation.

302

303 Similar to our study but using running tasks, Pinnington et al. (47) and Thomas and Derrick
304 (52) demonstrated alterations to kinematics on irregular surfaces. Thomas and Derrick (52)
305 found that runners demonstrated increased knee flexion at heel contact on an irregular surface,
306 with greater impact attenuation reported compared with a firm surface. Similarly, Pinnington
307 et al. (47) found that hip and knee flexion at initial foot contact (IFC), mid support (MS) and
308 flexion maximum were all greater when running on sand compared with firm surfaces at 8 and
309 11 km/h. Although joint angles were not analysed in the current investigation, it is possible that
310 the subjects landed with a greater degree of knee and hip flexion on the more unstable sand
311 surface in an attempt to improve stability on landing. As increased hip and knee flexion has
312 been shown to reduce anterior tibiofemoral shear force during a jumping task (53), these
313 kinematic changes may explain the reductions in AP tibial translation observed on the less
314 stable sand surface. Pinnington et al. (47) also demonstrated that the EMG of the hamstring
315 muscles was greater on sand during the late swing phase, which could be associated with a
316 need for greater eccentric control over the rate of knee extension, so that the knee remains more

317 flexed at IFC. EMG activity in the Hamstrings, Vastus Lateralis, Vastus Medialis, Rectus
318 Femoris and Tensor Fascia Latae were also greater than the firm surface measures during the
319 stance phase in the 8 km/h trials. These EMG findings suggest that repeated exposure to sand
320 or other less stable surfaces may lead to the development of muscle activation strategies that
321 promote stability and kinaesthetic sense during exercise, and subsequently reduce injury risk.
322 However, these changes were observed during running activities, and muscle activation
323 strategies may be different during the landing of jumping tasks on different surfaces. The role
324 of muscle control in protecting against ACL and PFJ injury has been previously established
325 with the importance of hamstring to quadriceps strength ratio and gastrocnemius strength
326 frequently cited (17,23,40,51). Further investigation of muscle activation strategies during the
327 four conditions tested here would be beneficial. This would help establish whether muscles
328 which are known to be important in reducing ACL injury risk have greater activation on a sand
329 compared to a firm surface during different jumping tasks.

330

331 Despite our findings, it is important to highlight potential limitations. We chose to use KAM
332 and AP tibial translation, as they were significant risk factors for PFJ and ACL injury.
333 However, as knee valgus has the greatest link to injury and can be screened clinically
334 (7,18,33,36,37), future studies which analyse knee valgus specifically, when comparing jump
335 landings onto sand and firm ground would be beneficial. To determine the effect of sand
336 specifically, rather than a less stable surface compared with a firm one, we acknowledge that
337 future studies should also include a more unstable control such as a pliable grass surface.

338

339 We used inverse dynamics to calculate the forces experienced by the subjects. This approach
340 does not consider individual muscle forces and their contributions to joint loading, so reduces

341 the accuracy in assessing the true forces acting on the joint. However, methods that accurately
342 measure individual muscles forces are not yet readily available, leaving inverse dynamics as a
343 suitable means of estimating joint forces at present. Although our pilot study showed that centre
344 of pressure measures would remain accurate with a sand covering on the force plate, we
345 acknowledge that the small offset between the depth of the footprint and the force plate may
346 have had some effect on our inverse dynamics calculations. Despite, the plug-in gait marker
347 set we used being widely utilised in biomechanical analysis for examining knee mechanics
348 (27,56), the authors feel that alternative marker sets may have been more appropriate for the
349 explosive nature of the movements being examined, for example those employed by Cappozzo
350 and colleagues (11) and Morgan and colleagues (40). We used a valid sampling frequency of
351 100 Hz for kinematic analysis of dynamics of the knee during loading, however we feel a
352 greater sampling frequency would have added strength to our study. A higher frequency would
353 have allowed the capture of all the forces during the weight-acceptance phase. These rapidly
354 rising forces (during the first 50_ms) are likely to be higher on the firm surface rather than the
355 sand. Hence, had we used a greater sampling frequency then the differences in KAM could
356 well have been even more apparent, further supporting the potential reduction in injury risk on
357 the less stable sand surface.

358

359 Sand characteristics such as granulation, moisture content, depth and consistency of the
360 substratum can contribute to different levels of stiffness and may affect results (46). As we
361 only used one type of sand under single lab-controlled conditions future work should quantify
362 the effects of different sand conditions on knee joint loads. Finally, use of state of the art
363 expensive technology such as the 3D Vicon system to quantify the kinetics observed lacks
364 ecological validity for practitioners, and would not be available in the clinical environment.
365 However, the Kinect is a valid and reliable tool for analysis (34).

366

367 Practical Applications

368 The present study adds to current understanding, showing some initial support for the use of a
369 less stable sand surface to reduce common knee joint loads associated with ACL and PFJ injury
370 during landing of both a drop (30_cm) and level jump. The data set is an initial step towards
371 determining whether sand may provide a safer alternative to firm ground in ACL and PFJ injury
372 prevention and rehabilitation programmes, which involve a jumping component. We showed
373 that both KAM and AP tibial translation were lower on sand compared to a firm surface during
374 drop and horizontal jump landings respectively. Strength and Conditioning professionals and
375 clinicians may therefore wish to consider the use of a less stable sand surface when planning
376 ACL or PFJ injury prevention or rehabilitation programmes which involve a dynamic jumping
377 component. The reduced loads in sand may have the potential to reduce ACL and PFJ injury
378 risk, whilst also enabling an accelerated rehabilitation program, as jumping activities could
379 potentially be implemented more safely at an earlier stage in the process. Further research is
380 required however, before any firm conclusions regarding the safety of a sand surface can be
381 made. We hope our study catalyses further research in this field.

382

383

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384

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387 endorsement of the product by the authors or the National Strength and Conditioning
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