1	Lower-limb muscle function during sidestep cutting		
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27 ABSTRACT

28	To investigate lower-limb muscle function during sidestep cutting, prior studies have
29	analysed electromyography (EMG) data together with three dimensional motion analysis.
30	Such an approach does not directly quantify the biomechanical role of individual lower-limb
31	muscles during a sidestep cut. This study recorded three dimensional motion analysis, ground
32	reaction force (GRF) and EMG data for eight healthy males executing an unanticipated
33	sidestep cut. Using a musculoskeletal modelling approach, muscle function was determined
34	by computing the muscle contributions to the GRFs and lower-limb joint moments. We found
35	that bodyweight support (vertical GRF) was primarily provided by the vasti, gluteus
36	maximus, soleus and gastrocnemius. These same muscles, along with the hamstrings, were
37	also primarily responsible for modulating braking and propulsion (anteroposterior GRF). The
38	vasti, gluteus maximus and gluteus medius were the key muscles for accelerating the centre-
39	of-mass towards the desired cutting direction by generating a medially-directed GRF. Our
40	findings have implications for designing retraining programs to improve sidestep cutting
41	technique.
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61 1. Introduction

Sidestep cutting is frequently performed in sports such as football (Bloomfield et al., 2007), 62 63 rugby (Green et al., 2011), and handball (Karcher and Buchheit, 2014). The ability to cut quickly and effectively is critical to overall performance in these sports. Sidestep cutting 64 technique has also been linked with musculoskeletal injury, such as anterior cruciate ligament 65 66 (ACL) injuries (Boden et al., 2000; Koga et al., 2010; Olsen et al., 2004). Less attention, 67 however, has been placed on understanding the fundamental roles of individual lower-limb 68 muscles during this type of change-in-direction manoeuvre. Such knowledge could be 69 important for designing retraining programs to improve sidestep cutting technique.

The execution of locomotion tasks requires the coordination of multiple muscles, since no single muscle can perform all biomechanical functions (Zajac et al., 2002). Neptune and colleagues (Neptune et al., 1999) used surface electromyography (EMG) to provide insight into the role of multiple individual lower-limb muscles during sidestep cutting. However, inferring the biomechanical role of each muscle from EMG data alone is difficult, since the way individual muscles contribute to joint and segment accelerations can sometimes be counter intuitive due to "dynamic coupling" (Zajac and Gordon, 1989).

77 Muscle actuated simulations have been used previously to predict muscle function 78 during a variety of locomotion tasks (Dorn et al., 2012b; Hamner and Delp, 2013; Liu et al., 2008; Neptune et al., 2001). The contributions of individual lower-limb muscles to ground 79 80 reaction forces (GRFs) or centre of mass accelerations can be used to understand how 81 muscles achieve key biomechanical functions, such as bodyweight support and forward 82 progression. Such analyses have mostly been limited to walking (Anderson and Pandy, 2003; 83 Lim et al., 2013; Liu et al., 2006; Liu et al., 2008; Neptune et al., 2001; Pandy et al., 2010) 84 and running (Dorn et al., 2012b; Hamner and Delp, 2013) in a straight direction. It is possible that lower-limb muscle function during sidestep cutting is distinct from that during walking 85 and running, given the greater demands on accelerating the body's centre of mass in a medial 86 direction. Subsequently, the aim of this study was to investigate lower-limb muscle function 87 88 during a rapid sidestep cut. Specifically, we used a computational musculoskeletal modelling 89 approach involving a GRF decomposition analysis (Dorn et al., 2012a; Dorn et al., 2012b; 90 Lin et al., 2011) to determine muscular contributions to bodyweight support, forward 91 progression and acceleration of the centre-of-mass in the desired direction of travel during an 92 unanticipated sidestep cut.

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95 **2. Methods**

96 2.1. Participants

97 Eight recreationally healthy males (age, 27 ± 3.8 years; height, 1.77 ± 0.09m; mass, 77.6 ±
98 12.8kg) volunteered to participate in this study. All participants had no current or previous
99 musculoskeletal injury likely to influence their ability to perform the required tasks. All
100 participants provided written informed consent to participate in the study. Ethical approval
101 was granted by the Australian Catholic University Human Research Ethics Committee
102 (approval number: 2015-11H).

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104 2.2. Instrumentation

105 Three-dimensional marker trajectories were recorded at 200Hz using a 9-camera motion

106 analysis system (VICON, Oxford Metrics Ltd., Oxford, United Kingdom). GRFs were

107 recorded via two ground-embedded force plates (Advanced Mechanical Technology Inc.,

108 Watertown, MA, USA) sampling at 1000Hz. Surface EMG signals were recorded at 1000Hz

109 from 10 lower-limb muscles on the dominant leg (defined as the kicking leg; right side for all

110 participants) via two telemetered EMG systems (Noraxon, Arizona, USA; Myon,

- 111 Schwarzenberg, Switzerland).
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113 2.3. Procedures

114 All participants completed the tasks while barefoot to allow exposure of the foot for marker placement and to avoid any variability in the foot-ground interface. The skin was prepared for 115 116 recording surface EMG signals by shaving, abrasion and sterilisation. Circular bipolar pre-117 gelled Ag/AgCl electrodes (inter-electrode distance of 2cm) were then placed on the vastus 118 lateralis and medialis, rectus femoris, biceps femoris, medial hamstrings, medial and lateral 119 gastrocnemius, soleus, tibialis anterior and peroneus longus muscles in accordance with 120 Surface Electromyography for the Non-Invasive Assessment of Muscle (SENIAM) 121 guidelines (Hermens et al., 2000). EMG-time traces during forceful isometric contractions 122 were visually inspected to verify the correct placement of the electrodes and to inspect for 123 cross-talk. Forty-three 14 mm retroreflective markers were affixed to each participant on 124 various anatomical locations (Maniar et al., 2018), including the torso (sternum, spinous process of the 7th cervical vertebra, spinous process of a mid-thoracic vertebra, tip of each 125 126 acromion), pelvis (anterior and posterior superior iliac spines), both upper-limbs (medial and 127 lateral elbow and distal radius and ulna) and both lower-limbs (medial and lateral femoral

epicondyles, medial and lateral malleoli, first and fifth metatarsophalangeal joints, calcaneusand three additional markers on each shank and thigh).

130 Each participant completed unanticipated change-of-direction tasks on their dominant 131 (right) leg (Maniar et al., 2018). Participants were required to perform two single leg hops for 132 a standardised distance of 1.35m, and then as quickly as possible cut to the left (45-degree 133 sidestep cut) or to the right (45-degree crossover cut) upon landing from the second hop. We 134 used a hopping approach based on prior research (Benoit et al., 2006) because it allows speed 135 and foot placement on the force plate to be well controlled across participants relative to a 136 running approach. The direction of travel was randomly dictated by a set of timing gates that 137 delivered a light signal ~450ms prior to initial contact on the force plates. Floor markings 138 were used to indicate the starting point, the hop landing targets and the required 45-degree angle from the force plates for the cutting direction. A successful trial required that the 139 participant completed the task correctly with the entire foot landing within the force plate. 140 141 Note that the 45-degree sidestep cut was the task of interest for this investigation, whereas the 142 crossover cut was only included to ensure cutting direction was unanticipated.

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144 2.4. Data processing

145 Marker trajectories were low-pass filtered using a zero-lag, 4th order Butterworth filter with a

146 cut-off frequency of 8Hz. This cut-off frequency was determined via a residual analysis.

147 GRFs were filtered using the same filter and cut-off frequency as the marker data based on

148 published recommendations (Kristianslund et al., 2012). EMG data were corrected for offset,

high-pass filtered (20Hz), full-wave rectified and low-pass filtered (6Hz) using a zero-lag, 4th

order Butterworth filter to obtain a linear envelope. EMG data were normalised to the peakamplitude obtained in each trial.

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153 2.5. Musculoskeletal modelling

A 29 degree-of-freedom (DOF) full-body musculoskeletal model, with 80 musculotendon 154 155 actuators (lower body) and 17 torque actuators (upper body) (Rajagopal et al., 2016), was 156 used to perform the musculoskeletal simulations in OpenSim (Delp et al., 2007). Each hip 157 was modelled as a 3-DOF ball-and-socket joint. Each knee was modelled as a 1-DOF hinge 158 joint, with other rotational (valgus/varus and internal/external rotation) and translational (anteroposterior and superior-inferior) movements constrained to change as a function of the 159 knee flexion angle (Walker et al., 1988). A pin joint was used to represent the ankle 160 161 (talocrural) joint. The head-trunk segment was modelled as a single rigid segment,

162 articulating with the pelvis via a 3-DOF ball-and-socket back joint. Each upper limb was characterised by a 3-DOF ball-and-socket shoulder joint and single-DOF elbow and 163 164 radioulnar joints. The generic model was scaled to each participant's individual anthropometry as determined during a static trial. An inverse kinematics algorithm was used 165 166 to calculate joint angles by means of a weighted least-squares optimisation that minimised the 167 difference between model and experimental marker positions (Lu and O'connor, 1999). A 168 residual reduction algorithm (RRA) was then used to make small adjustments to kinematics 169 and torso mass properties to improve dynamic consistency between kinematic data and 170 measured GRFs. Muscle forces were obtained via static optimisation, which decomposed the 171 RRA-derived joint moments into individual muscle forces by minimising the sum of muscle 172 activations squared, taking into account the physiological force-length-velocity properties 173 (Millard et al., 2013) of the musculotendinous units. This method of muscle force estimation 174 is computationally efficient and has been used to predict muscle forces in similar high impact 175 movements (Dorn et al., 2012b; Mokhtarzadeh et al., 2014; Mokhtarzadeh et al., 2013). We 176 then performed a GRF decomposition analysis (Dorn et al., 2012a; Dorn et al., 2012b; Lin et 177 al., 2011) to determine muscular contributions to the GRFs.

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179 2.6. Outcome variables

180 Muscular contributions to "support" as well as "braking and propulsion" are typically defined 181 by their contributions to the vertical and anteroposterior GRFs, respectively. However, these 182 definitions have been applied for planar tasks such as walking and running (Dorn et al., 183 2012b; Hamner and Delp, 2013; Liu et al., 2008; Neptune et al., 2001). Change of direction 184 manoeuvres require appreciable acceleration of the body's centre-of-mass out of the sagittal 185 plane, thus muscular contributions to the mediolateral GRF were also considered. These GRFs were expressed in the global reference frame. Finally, consistent with other studies 186 187 investigating muscle function (e.g. (Dorn et al., 2012b; Pandy et al., 2010)), we calculated 188 muscular contributions to lower-limb joint moments.

Certain muscles were combined into functional groups consistent with prior research (Sritharan et al., 2012). Note that we only report on major muscle groups, and did not report on muscles that were not found to make meaningful contributions to the outcome variables (see (Rajagopal et al., 2016) for all musculotendinous actuators included in the model). We also note that swing limb muscles made no meaningful contributions to the GRF, thus we only report on stance limb muscles.

195 2.7. Validation and verification

196 Validation and verification of model predictions was performed in accordance with current 197 best practice guidelines (Hicks et al., 2015). Qualitative comparisons between model-based 198 predicted muscle activations and experimental EMG recordings showed good agreement after 199 accounting for appropriate physiological delays of ~10-100ms (Figure 1). Additionally, the 200 time-varying characteristics of our RRA-derived joint angles (Supplementary Fig. S1) and 201 joint moments (Supplementary Fig. S2) were within 2SD of published data (Benoit et al., 202 2006; Oliveira et al., 2013; Sigward and Powers, 2006). Comparisons between experimental 203 and simulated variables were evaluated via the normalised root-mean-square error (nRMSE) and coefficient of determination (R^2) . The nRMSE was calculated as: 204

205 (1) nRMSE = 100 ×
$$\frac{\sqrt{\sum_{i=1}^{n} (Experimental_{i} - Predicted_{i})^{2}}}{\max(Experimental) - \min(Experimental)}$$

Muscle-derived joint moments (computed from the predicted muscle forces and their respective moment arms) were well matched with the experimental joint moments (median \pm interquartile range, R² = 1.0 \pm 0.0; nRMSE = 2.0 x 10⁻² \pm 0.03%). Superposition errors between experimental and simulated GRFs were also well matched (R² = 0.93 \pm 0.06; nRMSE = 9.8 \pm 3.7%). Residual forces and moments (Supplementary Fig. S3) and kinematic tracking errors (Supplementary Table 1) were also within recommended thresholds (Hicks et al., 2015).

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214 **3. Results**

215 3.1. Braking and propulsion

216 Anteroposterior GRFs were characterised by a braking force (posteriorly-directed GRF) in 217 the first half of stance, and propulsion (anteriorly-directed GRF) in the second half (Figure 218 2A). The anteroposterior GRF was primarily modulated by the hip extensors, knee extensors 219 and the ankle plantar flexors. Specifically, braking throughout stance was primarily generated 220 by the vasti (up to 335N) and soleus (up to 151N) muscle groups. The hip extensors were the 221 primary contributors to propulsion for the first ~60% of stance, with the gluteus maximus and 222 hamstrings producing up to 142N and 102N of the anteriorly-directed GRF, respectively. The 223 contributions of these two muscle groups declined thereafter, with the ankle plantar-flexors 224 taking over as the dominant contributors to propulsion (gastrocnemius, up to 312N; soleus, up to 93N). 225 226 227

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229 3.2. Vertical support

230 Vertical support was primarily generated by the gluteus maximus, vasti, soleus and

231 gastrocnemius (Figure 2B). The gluteus maximus was the dominant contributor to vertical

support in the first ~10% of stance, and produced up to 356N of vertical GRF at ~25% of

stance. This contribution declined thereafter. The vasti and soleus became the primary

vertical support muscles from ~10% to ~75% of stance, producing up to 1091N and 704N of

vertical force, respectively. The gastrocnemius produced up to 548N at ~80% of stance, and

- 236 declined thereafter along with the contributions from the vasti and soleus.
- 237

238 3.3. Mediolateral redirection

239 The net GRF was medially-directed throughout stance, indicating acceleration of the centre-240 of-mass towards the desired cutting direction (Figure 2C). Medial acceleration of the centre-241 of-mass was generated primarily by the vasti, gluteus maximus, and gluteus medius. The 242 vasti produced up to 424N of the medially-directed GRF, peaking at ~75% of stance. Also, 243 the gluteus maximus and medius respectively produced up to 105N and 96N of the mediallydirected GRF. The gastrocnemius and adductors generated a laterally-directed GRF (thereby 244 245 opposing acceleration of the centre-of-mass in the direction of travel), with these muscles 246 producing up to 147N and 102N, respectively, during late stance. In the last 15% of stance, 247 both the gastrocnemius and soleus accelerated the centre-of-mass medially, although these 248 contributions were no greater than 55N and 15N, respectively.

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250 3.4. Muscle contributions to lower-limb joint moments

251 Overall, the major contributors to the GRFs were also the major contributors to the net joint 252 moments (Figure 3). Muscles that contributed to propulsion tended to contribute to the hip 253 extension, knee flexion or ankle plantar flexion moments. The exception was soleus, which 254 was the dominant contributor to the ankle plantar flexion moment during the first half of 255 stance (Figure 3E), but it contributed to braking (posteriorly-directed GRF) during this period 256 (Figure 2A). The muscles that were responsible for vertical support tended to be the major 257 contributors to the hip extension, knee extension, or ankle plantar flexion moments. The 258 biarticular hamstrings, however, provided an appreciable contribution to the hip extension 259 moment (Figure 3A), but were responsible more so for generating propulsion rather than vertical support (Figure 2B). The gluteus medius and maximus were the dominant 260 261 contributors to the hip abductor moment, whereas the hip adductors contributed to the hip 262 adductor moment at the start and end of stance (Figure 3B).

263 4. Discussion

The purpose of this study was to evaluate lower-limb muscle function during an
unanticipated sidestep cut. Our main findings were as follows: firstly, braking and propulsion
as well as vertical support during a sidestep cut were primarily modulated by the vasti,
gluteus maximus, soleus, and gastrocnemius muscles; and secondly, by contributing to the
medial GRF, the vasti, gluteus maximus and gluteus medius were the most important muscles
for accelerating the centre-of-mass towards the desired cutting direction.

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271 4.1. Vertical support

272 To our knowledge, no previous studies have used computational musculoskeletal modelling 273 to quantify the contributions of individual lower limb muscles to the GRFs during sidestep 274 cutting. We have therefore compared our data with prior studies investigating walking 275 (Anderson and Pandy, 2003; John et al., 2012; Lim et al., 2013; Liu et al., 2006; Neptune et 276 al., 2004; Pandy et al., 2010) and running (Dorn et al., 2012b; Hamner and Delp, 2013) in a 277 straight line as well as turning gait (Dixon et al., 2015; Ventura et al., 2015). For example, 278 these studies have consistently found that vertical support is generated by the vasti and 279 gluteus maximus during early stance, after which the gastrocnemius and soleus become the 280 dominant contributors to vertical support. Our observations were similar (Figure 2B), 281 although we found that the relative contributions of these muscle groups were different 282 during sidestep cutting. Specifically, we found that the vasti made relatively larger 283 contributions to vertical support than the ankle plantar flexors, whereas the opposite has 284 typically been reported for walking (Anderson and Pandy, 2003; Lim et al., 2013; Liu et al., 285 2006; Neptune et al., 2004) and running (Dorn et al., 2012b; Hamner and Delp, 2013). These 286 observed differences could reflect the specificity of muscle function during sidestep cutting. 287 For example, the sidestep cut requires a larger medially-directed GRF compared to walking 288 (John et al., 2012) and running (Hamner et al., 2013). Since soleus generated a laterallydirected GRF for the majority of stance (Figure 2C), there may have been an overall shift in 289 290 strategy towards greater reliance on the vasti, which produced a medially-directed GRF 291 (Figure 2C). This explanation is supported by the similar peak soleus muscles forces but 292 substantially higher peak vasti muscle forces in the present study (Supplementary Fig. S4) when compared to running (Dorn et al., 2012b). Nevertheless, we acknowledge that these 293 294 differences could also be attributable to specific modelling techniques. For example, Dorn and colleagues (Dorn et al., 2012a) found that certain foot-ground contact models predict 295

296 greater contributions to vertical support from the vasti compared to the soleus during running,297 whilst other ground-contact models predict the opposite.

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299 4.2. Mediolateral redirection

300 We found that the vasti, gluteus maximus and gluteus medius were the dominant contributors 301 to redirecting the centre-of-mass acceleration towards the direction of travel in the frontal 302 plane via their contribution to the medially-directed GRF (Figure 2C). In contrast, the ankle 303 plantar flexors and the adductors were primarily responsible for accelerating the centre-of-304 mass in the opposite direction (Figure 2C). Whilst these functional roles are mostly similar to 305 previous investigations of walking (John et al., 2012; Lim et al., 2013; Pandy et al., 2010), 306 our observation that the vasti contributes to a medially-directed GRF is in contrast to prior 307 literature for walking (John et al., 2012; Lim et al., 2013; Pandy et al., 2010) and turning gait 308 (Ventura et al., 2015). The way in which a muscle force results in segment accelerations is 309 dependent on the configuration of the various joints in the system (Zajac and Gordon, 1989). 310 Hence, the differing segmental orientations (i.e. whole body kinematics) between sidestep 311 cutting compared to walking and running (Hamner et al., 2010; Liu et al., 2008) may explain 312 the differing roles between these locomotor tasks. For example, the stance leg was abducted 313 during sidestep cutting (Supplementary Fig. S1), whereas the stance leg is adducted during walking (Liu et al., 2008). These contrasting limb orientations could redirect the net 314 315 contribution from the vasti to involve acceleration of the centre-of-mass vertically and 316 medially during sidestep cutting compared to vertically and laterally during walking (John et 317 al., 2012; Lim et al., 2013; Pandy et al., 2010).

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319 4.3. Braking and propulsion

We found that braking (posteriorly-directed GRF) was primarily generated by the vasti 320 321 throughout stance and by the soleus during the first ~60% of stance, whereas propulsion 322 (anteriorly-directed GRF) was primarily generated by the gluteus maximus and hamstrings 323 during the first 60-70% of stance, and the gastrocnemius and soleus during late stance. Whilst 324 these findings are generally consistent with that for other forms of locomotion (Hamner and 325 Delp, 2013; Lim et al., 2013; Liu et al., 2006; Liu et al., 2008; Neptune et al., 2004), previous 326 studies have typically found that the gluteus maximus primarily accelerates the centre-of-327 mass posteriorly. As previously discussed, this contrasting result is probably attributable to differing segmental orientations (Zajac and Gordon, 1989) in sidestep cutting compared to 328

walking and running (Hamner and Delp, 2013; Liu et al., 2008).

330 4.4. Sidestep cutting performance

331 Determining the specific role of each muscle in the coordination of a rapid sidestep cut may 332 have implications for sidestep cutting performance. For example, prior studies have shown 333 that a greater peak ankle plantar flexor moment (Havens and Sigward, 2015; Marshall et al., 334 2014) and peak ankle power generation (Marshall et al., 2014) are associated with faster 335 sidestep cutting times. Our data concur with these results, as we found that the main ankle 336 plantar flexors (gastrocnemius and soleus) played a critical role in vertical support, and were 337 the dominant generators of propulsion during late stance (Figure 2A). Additionally, these 338 muscles were also found to have an important role in accelerating the centre-of-mass towards 339 the desired cutting direction, via their contributions to a medially directed GRF during the 340 final 15% of stance (Figure 2C). Havens and colleagues (Havens and Sigward, 2015) also 341 found that greater sagittal hip power generation was associated with faster sidestep cuts. Our 342 data also support the importance of the hip extensors (gluteus maximus and hamstrings), as 343 these muscle were main generators of propulsion during the first 60% of stance. Additionally, 344 the gluteus maximus was also found to contribute to vertical support as well as acceleration 345 of the centre-of-mass towards the desired cutting direction, demonstrating the importance of 346 this muscle for sidestep cutting performance.

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348 4.5. Implications

349 Our data may also help inform neuromuscular training interventions, which aim to minimise injury risk and maximise performance. For example, rapid change-in-direction tasks are a 350 351 common mechanism of ACL injury (Boden et al., 2000; Koga et al., 2010; Olsen et al., 2004) 352 and previous studies have shown that quadriceps and hamstring muscle forces tend to load 353 and unload the ACL, respectively. Our data show that the vasti play a fundamental role in 354 supporting bodyweight and accelerating the centre-of-mass towards the desired cutting 355 direction. This finding suggests that maximising quadriceps force production may be critical 356 for optimal performance, but it could also expose the ACL to greater load. In addition to their 357 role in protecting the ACL from these quadriceps forces (Li et al., 1999), our data suggest 358 that the hamstrings contribute to propulsion (anteriorly-directed GRF) during the first two 359 thirds of stance. It is therefore possible that facilitating hamstrings function during sidestep 360 cutting has the benefit of minimising injury risk without impairing performance. Further 361 research, however, is needed to verify this assertion.

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364 4.6. Limitations

The present study involved a cohort of eight healthy recreationally-active males. Further research should consider the influence of different populations such as females, specific athletic subgroups, and people with pathology. Additionally, only 45-degree sidestep cutting was investigated. It is possible that greater or smaller cutting angles would alter muscle coordination strategies, which therefore warrants further study.

370 Muscle forces in the present study were estimated using a static optimisation 371 approach, which does have some limitations. Unfortunately, muscle forces cannot be directly 372 validated because in-vivo muscle forces are not practically feasible to measure (Pandy and 373 Andriacchi, 2010), thus we have no way of directly validating our model predictions. Static 374 optimisation has been shown to be capable of providing accurate predictions of in-vivo joint 375 contact forces at least for walking (Lerner et al., 2015; Wesseling et al., 2015), which serves 376 as an indirect validation due to the high dependency of joint contact forces on muscle forces 377 (Pandy and Andriacchi, 2010). Furthermore, our predicted muscle activations showed 378 reasonable agreement with experimentally recorded EMG data across the stance phase 379 (Figure 1). It has been suggested that static optimisation may not adequately predict co-380 contraction of muscles. However, our predicted muscle activations, as well as recently 381 published data (Mokhtarzadeh et al., 2014), provide evidence of co-contraction. Nevertheless, 382 we recognise that these co-contraction patterns were not necessarily subject-specific, but we 383 do not believe this limitation influenced our conclusions. Further research utilising alternative 384 modelling approaches, such as EMG-driven (Pizzolato et al., 2015) and EMG-hybrid (Sartori 385 et al., 2014) models, may yield further insight.

386 We also acknowledge that the GRF decomposition technique relies on a ground-387 contact model that is susceptible to modelling errors (Lin et al., 2011) and can influence the interpretation of muscle function (Dorn et al., 2012a). However, the ground contact model 388 389 implemented in the present study allowed for a foot-phase-specific constraint set that is more 390 likely to be robust against various foot-strike patterns (Lin et al., 2011). Additionally, 391 verification of our outcomes via the principle of superposition indicated that our model 392 adequately reproduced experimentally measured GRFs, providing further confidence in the 393 suitability of the ground contact model.

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395 **5.** Conclusion

In summary, this study investigated lower-limb muscle function during a rapid sidestep cut.We found that the vasti, gluteus maximus, soleus, gastrocnemius and hamstrings were

398	important for modulating anteroposterior progression during the stance phase of an			
399	unanticipated sidestep cut. These same muscles (except the hamstrings) were also important			
400	for supporting bodyweight, while the vasti, gluteus maximus and the gluteus medius played a			
401	critical role in accelerating the centre-of-mass towards the desired cutting direction. These			
402	functional roles should be considered in neuromuscular retraining programs which aim to			
403	reduce injury risk and/or maximise performance.			
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- 564

565	Author Contributions
566	Conception of experimental procedures - NM, AGS & DAO. Conception of data analysis -
567	NM & AGS. Data collection and analysis – NM. Preparation of Figures – NM. Interpretation
568	of data - NM, AGS, MHC & DAO. Writing of manuscript - NM, AGS, MHC & DAO.
569	
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576	Figure captions
577	Figure 1. Comparison of predicted (black line) and experimental activations (grey shaded)
578	from the current data for the stance phase of the 45° unanticipated sidestep cut. Literature
579	reference activations, magenta dashed line, Neptune et al., 1999; blue dashed line, Beaulieu et
580	al., 2009. Panels, A, biceps femoris long head; B, medial hamstrings (semimembranosus and
581	semitendinosus); C, vastus medialis; D, vastus lateralis; E, rectus femoris; F, soleus; G,
582	gastrocnemius medialis; H, gastrocnemius lateralis; I, tibialis anterior; J, peroneus longus; K,
583	adductor magnus; L, gluteus maximus; M, gluteus medius.
584	
585	Figure 2. Muscular contributions to ground reaction forces for the stance phase of the 45°
586	unanticipated sidestep cut. Panel A, anteroposterior; B, superior-inferior; C, mediolateral.
587	Note that the shaded grey represents the net experimental value. SOLEUS, soleus; VASTI,
588	vasti (sum of vastus medialis, lateralis and intermedius); ADD, adductors (sum of adductor
589	brevis, longus and magnus); GMAX, gluteus maximus; GMED, gluteus medius; GAS,
590	gastrocnemius (sum of gastrocnemius medialis and lateralis); HAM, hamstrings (sum of
591	biceps femoris long head, semimembranosus and semitendinosus).
592	
593	Figure 3. Muscular contributions to the lower-limb net joint moments for the stance phase of
594	a 45° unanticipated sidestep cut. Note that the shaded grey represents the net experimental
595	value. HAM, hamstrings (sum of biceps femoris long head, semimembranosus and
596	semitendinosus); RECFEM, rectus femoris, GMAX, gluteus maximus; ILIOPSOAS,
597	iliopsoas (sum of iliacus and psoas major); GMED, gluteus medius; PIRI, piriformis; ADD,
598	adductors (sum of adductor brevis, longus and magnus); GMIN, gluteus minimus;

599 VASTI, vasti (sum of vastus medialis, lateralis and intermedius); GAS, gastrocnemius (sum
600 of gastrocnemius medialis and lateralis); SOLEUS, soleus.
601

Supplementary Figure 1. Joint angles computed via inverse kinematics (IK) and the residual
reduction algorithm (RRA) for the stance phase of a 45-degree unanticipated sidestep cut.

Supplementary Figure 2. Lower-limb joint moments computed via inverse dynamics (ID) and
the residual reduction algorithm (RRA) for the stance phase of a 45-degree unanticipated
sidestep cut.

608

609 Supplementary Figure 3. Summary of residual forces and moments after residual reduction

610 algorithm for the stance phase of a 45-degree unanticipated sidestep cut. Panels, A, residual

611 forces across the stance phase; B, residual moments across the stance phase; C, density

612 distribution of root mean square errors for residual forces; D, density distribution of root

613 mean square errors for residual moments; E, density distribution of maximum residual forces;

614 F, density distribution of maximum residual moments.

615

616 Supplementary Figure 4. Musculotendinous powers (top row) and forces (bottom row) for

617 muscles that were primary contributors to the ground reaction forces for the stance phase of a

618 45° unanticipated sidestep cut. VASINT, vastus intermedius; VASLAT, vastus lateralis;

619 VASMED, vastus medialis; GASLAT, gastrocnemius lateralis; GASMED, gastrocnemius

620 medialis.

621

622 Supplementary Figure 5. Musculotendinous powers (top row) and forces (bottom row) for

623 muscles that were secondary contributors to the ground reaction forces for the stance phase of

624 a 45° unanticipated sidestep cut. BFLH, biceps femoris long head; SEMIM,

625 semimembranosus; SEMIT, semitendinosus; ADDMAG, adductor magnus; ADDLONG,

adductor longus; ADDBREV, adductor brevis. Note the smaller y-axis scale compared to

627 Supplementary Figure 4.

628

629

630

631



0+ 0 50 75 25 Stance (%)

100

Α

Ε

I

Μ









Α



В



SOLEUS VASTI ADD GMAX GMED GAS HAM

С











Α

Supplementary Material

The following figures show the joint kinematics (S1) and kinetics (S2) before and after the residual reduction algorithm (RRA). Residual forces and moments (S3) after RRA are also provided, as well as the muscultendinous powers and forces for the major musculotendinous actuators (S4 and S5). Table 1 also shows the errors between experimental and RRA derived kinematics.



Supplementary Figure 1. Joint angles computed via inverse kinematics (IK) and the residual reduction algorithm (RRA) for the stance phase of a 45-degree unanticipated sidestep cut.



Supplementary Figure 2. Lower-limb joint moments computed via inverse dynamics (ID) and the residual reduction algorithm (RRA) for the stance phase of a 45-degree unanticipated sidestep cut.



Supplementary Figure 3. Summary of residual forces and moments after residual reduction algorithm for the stance phase of a 45-degree unanticipated sidestep cut. Panels, A, residual forces across the stance phase; B, residual moments across the stance phase; C, density distribution of root mean square errors for residual forces; D, density distribution of root mean square errors for residual moments; E, density distribution of maximum residual forces; F, density distribution of maximum residual moments.



Supplementary Figure 4. Musculotendinous powers (top row) and forces (bottom row) for muscles that were primary contributors to the ground reaction forces for the stance phase of a 45° unanticipated sidestep cut. VASINT, vastus intermedius; VASLAT, vastus lateralis; VASMED, vastus medialis; GASLAT, gastrocnemius lateralis; GASMED, gastrocnemius medialis.



Supplementary Figure 5. Musculotendinous powers (top row) and forces (bottom row) for muscles that were secondary contributors to the ground reaction forces for the stance phase of a 45° unanticipated sidestep cut. BFLH, biceps femoris long head; SEMIM, semimembranosus; SEMIT, semitendinosus; ADDMAG, adductor magnus; ADDLONG, adductor longus; ADDBREV, adductor brevis. Note the smaller y-axis scale compared to Supplementary Figure 4.

Coordinate	Root mean square error	Max error		
	$(\text{mean} \pm \text{SD})$	$(\text{mean} \pm \text{SD})$		
Pelvis translation (cm)				
tx	1.0 ± 0.6	1.7 ± 0.9		
ty	2.4 ± 0.6	3.3 ± 0.8		
tz	0.8 ± 0.5	1.2 ± 0.7		
Pelvis rotation (°)				
Tilt	0.8 ± 0.5	1.5 ± 0.9		
List	0.8 ± 0.4	1.7 ± 1.0		
Rotation	0.9 ± 0.3	1.7 ± 0.5		
Hip rotation (°)				
Flexion	0.6 ± 0.3	1.6 ± 0.6		
Adduction	0.7 ± 0.2	1.3 ± 0.4		
Rotation	0.4 ± 0.2	1.2 ± 0.5		
Knee rotation (°)				
Flexion	0.7 ± 0.3	1.8 ± 0.7		
Ankle rotation (°)				
Flexion	1.3 ± 0.1	2.9 ± 0.4		
Note that the root mean square computations in this table were not normalised similar to				

Supplementary Table 1. Root mean square and maximum errors between joint positions derived from inverse kinematics and the residual reduction algorithm.

Note that the root mean square computations in this table were not normalised similar to other variables reported within the manuscript because currently recommended thresholds (Hicks et al. 2015) for the values reported in this table are typically reported in degrees and centimeters. tx, anteroposterior translation; ty, vertical translation; tz, mediolateral translation.