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1 **The effects of initial conditions and takeoff technique on**
2 **running jumps for height and distance**

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36 **Abstract**

37 This study used a subject-specific model with eight segments driven by joint
38 torques for forward dynamics simulation to investigate the effects of initial
39 conditions and takeoff technique on the performance of running jumps for
40 height and distance. The torque activation profiles were varied in order to
41 obtain matching simulations for two jumping performances (one for height and
42 one for distance) by an elite male high jumper, resulting in a simulated peak
43 height of 1.98 m and a simulated horizontal distance of 4.38 m. The peak
44 height reached / horizontal distance travelled by the mass centre for the same
45 corresponding initial conditions were then maximized by varying the activation
46 timings resulting in a peak height of 2.09 m and a horizontal distance of 4.67
47 m. In a further two optimizations the initial conditions were interchanged
48 giving a peak height of 1.78 m and a horizontal distance of 4.03 m. The four
49 optimized simulations show that even with similar approach speeds the initial
50 conditions at touchdown have a substantial effect on the resulting
51 performance. Whilst the takeoff phase is clearly important, unless the
52 approach phase and the subsequent touchdown conditions are close to
53 optimal then a jumper will be unable to compensate for touchdown condition
54 shortcomings during the short takeoff phase to achieve a performance close
55 to optimum.

56

57 **Introduction**

58 Running jumps are an integral part of many activities and can be generally
59 considered to consist of three main phases: the approach, the takeoff and the
60 flight phase (Greig and Yeadon, 2000). The takeoff is considered to be the
61 most important of the three phases while the approach phase is vital for its
62 preparation (Dapena, 1988). The main purpose of the approach phase is
63 therefore to place the athlete in the optimum initial conditions for the takeoff
64 phase. Due to the specific requirements of high jumping and long jumping
65 there are differences in athletes' optimal initial conditions. The optimal
66 approach speed for long jumping is faster than for high jumping where an
67 'intermediate' approach speed is optimal (Greig and Yeadon, 2000;
68 Alexander, 1990). Using a theoretical model, Alexander (1990) found that
69 long jumping has a steeper optimum plant angle (the angle between the
70 backward horizontal and the line joining the ankle and hip of the takeoff leg)
71 than in high jumping where the optimum plant angle is closer to the horizontal.
72 The shallower plant angle utilised by high jumpers facilitates the production of
73 vertical velocity. The steeper plant angle utilised in long jumping allows the
74 athlete to gain vertical velocity whilst maintaining a fast horizontal velocity
75 (Hay, 1981). Theoretically a straight plant leg is optimal for both high jumping
76 (Greig and Yeadon, 2000) and long jumping (Seyfarth et al., 2000) and a
77 greater backward lean of the trunk at touchdown is needed for high jumping
78 (Dapena, 1988), while in long jumping the trunk angle is closer to vertical
79 (Graham-Smith and Lees, 2005).

80

81 Differences primarily in initial conditions at touchdown lead to a shorter takeoff
82 phase of around 120 ms for long jumping (Seyfarth et al., 2000; Bridgett and
83 Linthorne, 2006) compared to a longer contact time of around 180 ms for high
84 jumping (Aura and Vittasalo, 1989). During the takeoff phase high jumpers try
85 to maximise gain in vertical velocity (Greig and Yeadon, 2000) while long
86 jumpers attempt to develop vertical velocity whilst limiting the inevitable loss in
87 horizontal velocity (van Don and Hay, 1994). The amount of knee flexion of
88 the takeoff leg during the final contact phase has been identified as one of the
89 factors that influence the production of vertical velocity (Dapena, 1980). In the
90 high jump the knee joint flexes to an angle in the region of 133° (Dapena,
91 1980) whereas in the long jump the knee flexes to approximately 140°
92 (Graham-Smith and Lees, 2005), although the effect of different approach
93 speeds on knee kinematics in each type of jump is not clear.

94

95 It is clear that both the approach phase (initial conditions at touchdown) and
96 the takeoff phase are critical for a successful performance of a running jump
97 for height or distance. The relationship between these two phases is complex
98 with it not being clear what effect changes in takeoff technique can have on
99 performance for a particular combination of approach characteristics. The
100 purpose of this study was to use a theoretical simulation model to investigate
101 the relative effects of initial conditions and takeoff technique on running jumps
102 for height and distance.

103

104 **Methods**

105 An international male high jumper of height 1.89 m and mass 82 kg, with a
106 personal competition best of 2.31 m was used as the subject in the study.
107 The athlete gave informed consent for the procedures which were carried out
108 in accordance with the protocol approved by Loughborough University Ethical
109 Advisory Committee. Ninety-five anthropometric measurements were taken
110 on the athlete and segmental inertia parameters were calculated using the
111 geometric inertia model of Yeadon (1990b). The athlete was requested to
112 perform a high jumping and a long jumping performance with similar approach
113 speeds. Both performances were recorded at a frequency of 200 Hz using
114 two video cameras (50-Hz Sony digital Handycam VX1000 camera and a
115 NAC high-speed HSV-400 video camera; Wilson et al., 2006). Fifteen body
116 landmarks (wrist, elbow, shoulder, hip, knee, ankle and toe joint centres of
117 both sides of the body, plus the centre of the head) were manually digitized
118 and were reconstructed using the Direct Linear Transformation algorithm
119 (Karara, 1980) with camera synchronisation effected using the digitised
120 landmark data (Yeadon and King, 1999). The coordinate data and the inertia
121 data were used to calculate the jumper's orientation and configuration angles
122 throughout the movements, along with the mass centre velocity and whole-
123 body angular momentum about the mass centre (Yeadon, 1990a, 1990c).
124 The time histories of the orientation and configuration angles were fitted using
125 quintic splines (Wood and Jennings, 1979) in order to obtain angle and
126 angular velocity estimates throughout the movements. Although the recorded
127 high jumping performance (Fosbury-flop) was three-dimensional in many
128 respects, the contact phase was essentially planar since the mean deviation
129 from the vertical plane through the mass centre path was less than 5°.

130

131 A planar eight-segment forward dynamics computer simulation model (King et
132 al., 2006) was used (Figure 1) for the foot contact phase in running jumps.
133 The eight segments comprised foot, shank and thigh of the takeoff leg, thigh
134 and shank + foot of the free leg, trunk + head, upper arm and lower arm +
135 hand (representing both arms). Wobbling masses situated within the shank
136 and thigh segments of the takeoff leg and trunk segment and the foot-ground
137 interface were modelled using non-linear spring-damper systems, the visco-
138 elastic parameters for which were determined using an angle-driven version of
139 the model (Wilson et al., 2006). Torque generators, comprising rotational
140 elastic and contractile elements in series, acted around five of the joints
141 (ankle, knee and hip of the takeoff leg; hip of the free leg and shoulder) with
142 extensors and flexors represented separately. The torque produced by a
143 torque generator during a simulation was given by the product of the
144 activation and the maximum voluntary joint torque function (of contractile
145 element angle and angular velocity) whose parameters were determined from
146 dynamometer measurements (King et al., 2006; Yeadon et al., 2006). The
147 activation of each torque generator ranged from 0 to 1 throughout a simulation
148 with the activation at a specific time specified by an activation time history
149 profile. The activation profiles were defined using 6 parameters for the
150 agonists of each joint and 5 parameters for the antagonists of each joint as
151 described in King et al. (2006). The parameters defined the timing of onset of
152 activation, the times to rise and fall between minimum and maximum
153 activation and the levels of minimum and maximum activation. The elbow and

154 free knee joint were driven using splined angle time histories of the recorded
155 jumps.

156

157 *** Figure 1 goes here ***

158

159 Input to the torque-driven model consisted of the kinematics at touchdown and
160 the activation time histories of the 10 torque generators. Model output
161 comprised the time histories of the foot-ground spring-damper displacements,
162 joint angles and trunk orientation from which mass centre position and velocity
163 together with angular momentum about the mass centre were calculated.

164

165 Two simulations which matched the recorded performances of the high jump
166 and long jump during the foot contact prior to takeoff were obtained by varying
167 the torque generator activation profiles in order to minimize the sum of a
168 difference score and various penalties. The difference score for each
169 simulation was the root mean square of six components based on the
170 difference between simulation and performance in terms of (1) trunk
171 orientation, (2) joint angles, (3) time of contact, (4) linear momentum, (5)
172 angular momentum and (6) height / distance travelled in flight (King et al.,
173 2006; Wilson et al., 2007). Penalties were used to ensure that the joint angles
174 remained within anatomical limits. The peak height reached by the mass
175 centre during the flight phase was determined using equations of constant
176 acceleration under gravity along with the height and vertical velocity of the
177 mass centre at takeoff. The horizontal distance travelled by the mass centre
178 during flight was determined using the assumption that the mass centre had

179 fallen to 0.6 m above the ground at the end of the jump based upon the
180 experimental data collected.

181

182 Following the generation of matching simulations for the high jump (match H)
183 and the long jump (match L) four optimizations were carried out. Using the
184 initial conditions from the respective matching simulations the peak height
185 reached by the mass centre in the high jump and the horizontal distance
186 travelled by the mass centre during the flight phase in the long jump were
187 maximized (opt HH and opt LL respectively) by varying the 55 torque
188 activation parameters within the optimization algorithm Simulated Annealing
189 (Corana et al., 1987). A further two optimizations were carried out in which
190 the initial conditions from the matching simulation of the high jump were used
191 in an optimization to maximize jump length (opt HL) and the initial conditions
192 from the matching simulation of the long jump were used in an optimization to
193 maximize jump height (opt LH). Perturbations to joint torque activation timings
194 of the knee and hip were incorporated in the optimization process to ensure
195 that a robust optimum solution was found in each case (Wilson et al., 2007).
196 In particular, the onset timings of the hip and knee extensor torque generators
197 were varied by ± 5 ms producing four additional simulations with the score
198 maximized taken to be the mean score of the four perturbed simulations. In
199 addition in all four optimizations the knee and ankle joint angles of the takeoff
200 leg were constrained to be less than 180° and 160° respectively both at
201 takeoff and during the first 100 ms of the flight phase assuming constant
202 angular acceleration (Wilson et al., 2007).

203 **Results**

204 The recorded high jumping and long jumping performances had similar
205 approach speeds of 7.4 ms^{-1} and 6.9 ms^{-1} respectively but different initial
206 configuration and orientation angles at touchdown (Table 1, Figure 2). The
207 different angles at touchdown resulted in a shallower plant angle of 53° (from
208 the backward horizontal) for the high jump compared to a plant angle of 60°
209 for the long jump.

210

211 *** Table 1, Figure 2 go here ***

212

213 The matching simulation of the high jump performance resulted in a peak
214 height of 1.98 m compared to the recorded peak height of 2.01 m, a difference
215 score of 6.9% and a horizontal distance travelled of 3.91 m (Table 2, Table 3).

216 The matching simulation of the long jump performance resulted in a horizontal
217 distance travelled of 4.38 m compared to the recorded distance of 4.58 m, a
218 difference score of 10.5% and a peak height of 1.65 m (Table 2, Table 3).

219 The torque activation profiles were similar for the two matching simulations
220 (Figure 3) although the time to peak knee extensor activation was
221 considerably shorter for match L compared to match H (0.051 s compared to
222 0.097 s) (Table 4).

223

224 *** Tables 2 and 3 go here ***

225 *** Figure 3 goes here ***

226

227 In opt HH the optimised peak height reached by the mass centre was 2.09 m
228 which corresponded to an increase of 0.11 m from the matching simulation
229 match H. In opt LL the optimised horizontal distance travelled by the mass
230 centre during the flight phase was 4.67 m which corresponded to an increase
231 of 0.29 m from the matching simulation. Optimising for the opposite
232 performance variable (opt LH and opt HL) had relatively small effects on the
233 peak height (0.02 m) or horizontal distance travelled (0.17 m) by the mass
234 centre during the flight phase (Table 3). The effect of the initial conditions was
235 much larger than the effect of the changed torque generator activation
236 technique with a 0.63 m greater distance travelled in opt LL compared with opt
237 HL even though the approach speed was greater for opt HL (Table 3). The
238 effect of the initial conditions was also greater than that of the takeoff
239 technique for the time of contact, for the mass centre position at takeoff (Table
240 3), for the knee and hip angle time histories of the takeoff leg (Figure 4) and
241 also the torque activation time histories (Table 4, Figure 5). In particular the
242 time taken for the knee extensors to reach maximum activation was clearly a
243 function of the initial conditions (0.096 s for opt HH / opt HL compared to
244 0.050 s for opt LL / opt LH). The hip extensor activation time history was
245 largely independent of both initial conditions and takeoff technique in the four
246 optimised simulations (Table 4, Figure 5). Furthermore, the knee angle time
247 histories for the two optimal jumps for height (opt HH and opt LH) had less
248 knee flexion than the equivalent optimal simulation for distance (opt LL and
249 opt HL) with the same initial conditions (Figure 4).

250

251

** Table 4 goes here**

252

** Figures 4 and 5 go here**

253

254 **Discussion**

255 The aim of this study was to investigate the relative effects of initial conditions
256 and takeoff technique on running jumps for height and distance. A planar
257 eight segment subject-specific computer simulation model was used to
258 simulate running jumps for height and distance with two different sets of initial
259 touchdown conditions and determine robust optimal solutions for height and
260 distance. Overall the effect of initial conditions was much greater than the
261 takeoff technique on the heights reached and distances jumped. The heights
262 and distances achieved in the optimised jumps (opt HH and opt LL) were 0.11
263 m and 0.29 m greater than the respective matching simulations suggesting
264 that for the given initial conditions the techniques used by the elite high jumper
265 were relatively close to optimal.

266

267 The two jumping performances used similar approach speeds but different
268 initial configuration and orientation angles at ground contact (Table 1). The
269 different angles at touchdown resulted in a shallower plant angle of 53° (from
270 the backward horizontal) for the high jump compared to a plant angle of 60°
271 for the long jump. The steeper angle used for the long jumping performance
272 agrees well with previous studies (Alexander, 1988; Hay, 1981) and suggests
273 that the elite high jumper used in this study had appropriate initial conditions
274 for the two jumps. Furthermore, the trunk orientation at touchdown was closer
275 to vertical in the long jumping performance which is in agreement with
276 previous studies (Dapena, 1988; Graham-Smith & Lees, 2005) where a

277 backward lean at touchdown in the high jump has previously been identified
278 as being advantageous to performance (Dapena, 1988). The clear
279 differences in initial configuration / orientation angles between the two
280 performances and agreement with the literature suggests that the elite high
281 jumper used in this study was able to adopt a close to optimal position at
282 touchdown for each jump while being restricted to use similar horizontal
283 approach speeds. As a consequence it would be expected that even with
284 optimal technique during the takeoff phase it would not be possible to
285 compensate for inappropriate initial conditions when the initial conditions were
286 interchanged (opt HL and opt LH).

287

288 The effect of takeoff technique was investigated by keeping the initial
289 conditions fixed and optimising for the alternative performance outcome (opt
290 HL and opt LH). Small effects (Table 3) of less than 0.06 m and 0.17 m
291 difference in the optimal solutions for peak height jumped / distance travelled
292 between opt HH – opt HL and opt LL – opt LH were found. This result
293 confirms that although the takeoff phase is important, it is not possible to
294 make up for inappropriate initial conditions by changing technique. In
295 addition, during the takeoff phase and in contrast to previous literature
296 (Dapena, 1980; Graham-Smith & Lees, 2005), the knee flexed to a greater
297 degree in the optimised long jumping performance (opt LL) compared to the
298 optimised high jumping performance (opt HH) (Figure 4). The reason for the
299 discrepancy may be the approach speeds used in the two optimal simulations
300 were similar when in reality the approach speed used in long jumping is
301 normally considerably faster than in high jumping (Alexander, 1990). In the

302 current study, comparing opt HH with opt HL and opt LL with opt LH also
303 showed that both optimal simulations for height (with the same approach
304 speed as the optimised simulations for distance) had slightly less knee flexion
305 than the two optimal simulations for distance.

306

307 The effect of the initial conditions was investigated by comparing the two
308 optimal solutions for height with different initial conditions (opt HH and opt LH)
309 and the two optimal solutions for distance with different initial conditions (opt
310 LL and opt HL). Both comparisons showed the same trend that the initial
311 conditions were crucial to a successful performance with a 0.27 m difference
312 in jump height (opt HH and opt LH) and a 0.63 m difference in distance
313 jumped (opt LL and opt HL). Consequently to achieve an optimal
314 performance requires an appropriate set of initial conditions at touchdown.

315 The effect of the initial conditions was also evident in the mass centre position
316 at takeoff (Table 3) with the initial conditions for a high jump giving a mass
317 centre position vertically above the foot for match H, opt HH and opt HL, while
318 the initial conditions for a long jump resulted in a mass centre position at
319 takeoff of approximately 0.38 m in front of the toes of the takeoff leg for match
320 L, opt LL and opt LH. This is in agreement with a previous study (Nagano et
321 al., 2007) where in jumps for height the mass centre was above the feet at
322 takeoff, but some distance in front of the feet for jumps for distance and
323 confirms that there is little that can be done during the short contact phase to
324 effect the path of the mass centre during the takeoff phase for a given set of
325 initial conditions at touchdown.

326

327 The general applicability of the study is potentially limited by the use of a
328 single elite subject and two performances: a running jump for height and a
329 running jump for distance with similar approach speeds. However, the two
330 performances in terms of initial configurations and orientation have been
331 shown to be consistent with previous studies and have resulted in distinct
332 optimal solutions for height and distance. In conclusion, the results of this
333 study suggest that it is the differences in initial conditions rather than takeoff
334 technique which have the greater influence on optimal jumping performance.
335 It is suggested that this is due to the distinct differences in optimal initial
336 conditions between the two jumps and the relatively short period of time in
337 which the takeoff technique can be adjusted to accommodate for changes in
338 optimal initial conditions. Whilst the takeoff phase is clearly important for the
339 successful performance of a jump and could be considered to be the most
340 important of the three phases of jumping, if the approach phase and the
341 subsequent initial conditions are not close to optimal then a jumper will be
342 unable to compensate for these shortcomings during the short takeoff phase
343 to achieve a jump height or jump distance close to optimum.

344

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Table 1. Initial conditions for matching simulations

variable	high jump	long jump	variable	high jump	long jump
v_{cmx}	7.40 ms^{-1}	6.87 ms^{-1}	v_{cm_y}	-0.58 ms^{-1}	-0.43 ms^{-1}
θ_a	85°	98°	$\dot{\theta}_a$	201°s^{-1}	28°s^{-1}
θ_k	157°	151°	$\dot{\theta}_k$	-58°s^{-1}	-162°s^{-1}
θ_h	141°	134°	$\dot{\theta}_h$	219°s^{-1}	-28°s^{-1}
θ_s	59°	-20°	$\dot{\theta}_s$	881°s^{-1}	518°s^{-1}
θ_e	92°	116°	$\dot{\theta}_e$	-1320°s^{-1}	156°s^{-1}
θ_m	209°	197°	$\dot{\theta}_m$	-228°s^{-1}	-796°s^{-1}
θ_{rk}	104°	127°	$\dot{\theta}_{rk}$	1271°s^{-1}	-460°s^{-1}
θ_t	80°	91°	$\dot{\theta}_t$	-46°s^{-1}	49°s^{-1}

Note: See Figure 1 for angle definitions, v_{cmx} and v_{cm_y} are the horizontal and vertical velocities of the mass centre at touchdown.

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Table 2. Details of the difference score for the matching simulations

	match H	match L
difference score	6.9%	10.5%
trunk orientation	7.7°	2.6°
joint angles	13.1°	19.0°
contact time	1.1%	11.7%
linear momentum	6.4%	11.4%
angular momentum	0.6%	0.0%
peak height	4.0%	
horizontal distance		4.3%

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Table 3. Mass centre location (CM_x , CM_z) at takeoff [m], horizontal and vertical velocities of the mass centre (VCM_x , VCM_z) at takeoff [ms^{-1}] and the heights and distances jumped [m]

	match H	match L	opt HH	opt LL	opt HL	opt LH
CM_x	0.00	0.37	0.06	0.38	-0.02	0.38
CM_z	1.28	1.20	1.27	1.25	1.29	1.24
VCM_x	4.30	5.72	4.02	5.61	4.27	5.45
VCM_z	3.71	2.98	4.00	3.30	3.91	3.37
height	1.98	1.65	2.09	1.80	2.06	1.82
distance	3.91	4.38	3.87	4.67	4.04	4.59

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Table 4. Time to maximal activation of the leg joint extensor torque generators

	time to maximal activation [s]					
	match H	match L	opt HH	opt LL	opt HL	opt LH
ankle	0.106	0.154	0.111	0.141	0.120	0.122
knee	0.097	0.051	0.096	0.050	0.096	0.050
hip	0.054	0.051	0.055	0.050	0.053	0.051

427
428

429 List of figure captions

430 Figure 1. Eight segment simulation model. Rigid links between joint centres
431 are shown as straight lines. Wobbling masses within the trunk and
432 plant leg thigh and shank segments are shown with bounding arcs.

433 Figure 2. Orientation and configuration at touchdown for (a) the high jump
434 and (b) the long jump performances.

435 Figure 3. Activation time histories for the ankle, knee and hip extensors
436 (black) and flexors (grey) in the matching simulations.

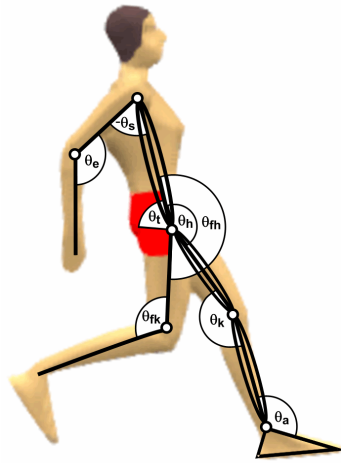
437 Figure 4. Joint angle time histories of the knee and hip for the four optimised
438 simulations. Initial conditions from the high jump and long jump
439 performances are shown with thick and thin lines respectively and
440 the solid lines correspond to opt HH and opt LL, while the dashed
441 lines correspond to opt HL and opt LH.

442 Figure 5. Activation time histories for the ankle, knee and hip extensors
443 (black) and flexors (grey) in (a) the optimisations for height (opt
444 HH) and distance (opt LL) with the initial conditions for high and
445 long jumps and (b) the optimisations for length (opt HL) and height
446 (opt LH) with the initial conditions for high and long jumps.

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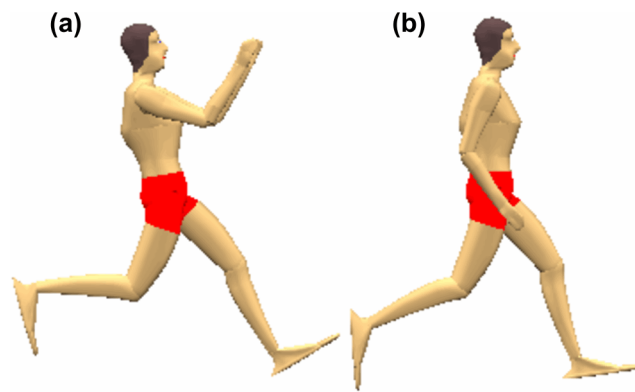
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463 Figure 1.

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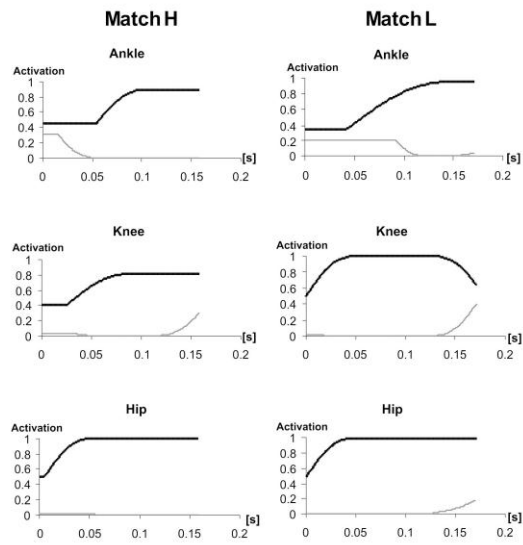
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475 Figure 2.

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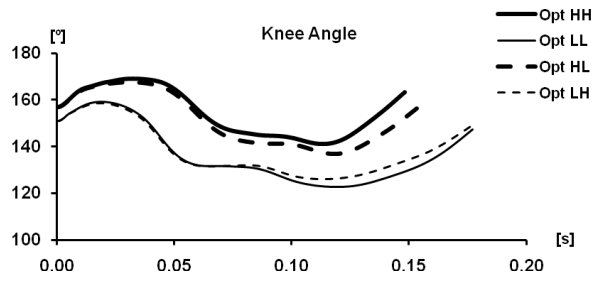
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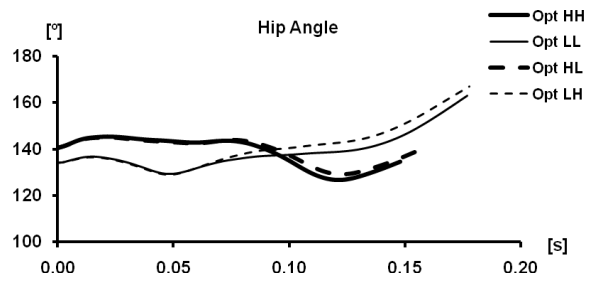
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487 Figure 3.

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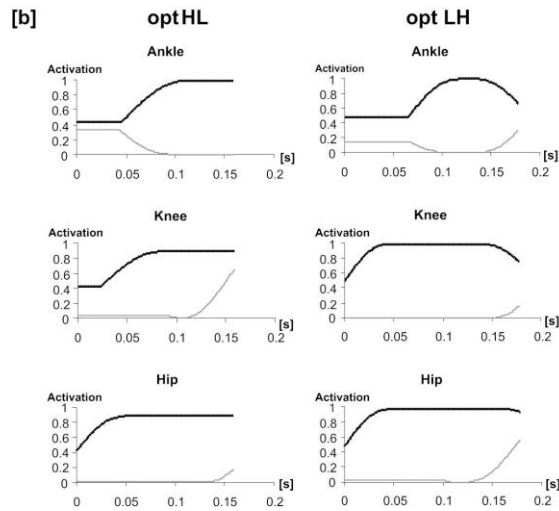
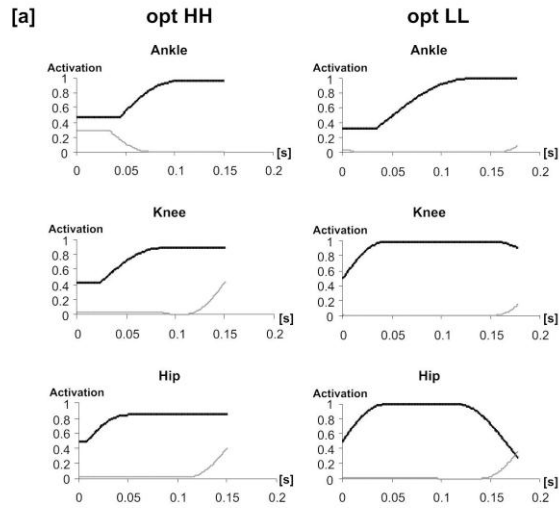
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500 Figure 4.

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Figure 5.