

1 **The effect of velocity-based loading on acceleration kinetics and kinematics**
2 **during sled towing**

3
4 **ABSTRACT**

5
6 Sled towing (ST) provides an external load in the form of a sled towed via a shoulder
7 or waist harness and cord, behind the athlete. Loading strategies have varied greatly
8 between studies and despite many investigations there is little agreement on the
9 optimum sled loading to develop the acceleration phase. The aim of this study was to
10 investigate the kinetics and kinematics of velocity-based ST during the acceleration
11 phase of sprinting. Twelve academy rugby league players performed a series of 6 m
12 sprints in different conditions; uninhibited, 10%, 15% and 20% velocity decrement
13 (V_{Dec}). Sagittal plane kinematics and kinetic measures were examined using one-way
14 repeated measures analysis of variance. Results indicated that ST affected trunk,
15 knee and ankle joint kinematics ($p < 0.05$). Peak knee flexion increased as sled loads
16 increased ($p < 0.05$), which may enable athletes to lower their centre of mass and
17 increase their horizontal force application. Net horizontal and propulsive impulse
18 measures were greater in all sled conditions ($p < 0.05$), which increased significantly
19 as sled loadings were heavier. In conclusion, this study highlights the effects of
20 differential loads to help coaches understand acute kinetics and kinematic changes in
21 order to improve the planning of sprint training.

22
23 **Keywords:** acceleration, biomechanics, kinematics, kinetics, sled towing

24 **Word count: 3944**

26 **INTRODUCTION**

27

28 Sprint acceleration is defined as the capacity to generate as high a velocity as possible
29 in as short a distance or time as possible (22), and is essential for success in the
30 majority of sports (14,29). In field sports, where the need to reach the ball first or be in
31 position for play to develop is decisive, acceleration is a crucial factor (22,29).
32 Maximum velocity may not be as important as sprint acceleration in field sport players
33 (29). The different sprint phases are regularly tested and monitored as they are
34 considered key determinants of overall sprint performance (31). Research shows that
35 rapid acceleration requires a powerful drive of the arms, hips and legs resulting in short
36 contact times and an increased stride frequency (24,29). Alternatively, other studies
37 have placed a greater emphasis on a forward body lean (45 degrees), thereby
38 increasing horizontal force application (16,20).

39

40 Coaches may improve acceleration in different ways; by incorporating strength
41 exercises (10), plyometric exercises (13) or with a more combined approach (9).
42 Programmes are generally focussed on either increasing an athlete's maximal
43 strength or power; however, coaches can also focus on movement efficiency or force
44 application (7). These modalities may have a better transfer to performance compared
45 to non-specific strength training (36). Resisted sprint training methods such as sled
46 towing (ST), parachutes, weighted vests, bungees and uphill running offer the coach
47 an alternative approach to sprint training. Resisted sprint training modalities are
48 performed in a horizontal direction, and involve the relevant muscles, velocities and
49 ranges of motion to those of uninhibited sprinting (1,35). Research suggests that such
50 sprint-specific training methods can lead to greater speed development (4). ST

51 provides an external load in the form of a sled towed via a shoulder or waist harness
52 and cord, behind the athlete. The mass of the sled and the friction coefficient between
53 the sled and the ground surface affect external load and the subsequent impact on
54 performance (21). Sleds are generally loaded based on a percentage of body mass
55 (BM) or percentage of velocity decrement (V_{Dec}) (3,17,35). However, loadings based
56 on a percentage BM do not account for individual variations in strength, power or
57 technical ability. As such, loading sleds based on V_{Dec} over a given distance is the
58 preferred approach (31).

59

60 Acute ST studies are important as they allow researchers to investigate how different
61 loading strategies can alter kinetics and kinematics. These acute changes may
62 determine long-term adaptations. Sled loading strategies have varied greatly between
63 studies, some researchers have investigated loads as light as 5% BM (30) and others
64 as heavy as 80% BM (27). Unsurprisingly, findings suggest that as sled loadings
65 increased, sprint kinematics (velocity, contact time, stride length and stride frequency
66 etc.) were changed to a greater extent (23,25,30). As such, some investigations have
67 recommended sled loadings of approximately 10% BM or 10% V_{Dec} in order to
68 minimise the alterations to sprint kinematics (24). However, recent investigations have
69 reported that moderate to heavy sled loadings may be required in order to provide an
70 optimal overload for sprint acceleration (25). These loadings may increase horizontal
71 ground reaction forces (GRF), which have been shown to be a key determinant of
72 sprint acceleration (26). Kinetics and lower body kinematics have been explored over
73 a range of different ST loads, despite numerous investigations (18,24,30) there is little
74 agreement on the optimum sled loading to develop the acceleration phase.

75

76 The purpose of this study was to investigate kinetics and kinematics of ST during the
77 early acceleration phase of sprinting in an elite academy rugby league population.
78 Participants completed trials with a range of different sled loads (10, 15 and 20% V_{Dec})
79 as well as uninhibited trials. It was hypothesised that (a) the disruption to lower limb
80 and trunk kinematics would increase as sled loadings increased, (b) propulsive peak
81 force would be greatest during the 20% V_{Dec} sled trials, and (c) propulsive impulses
82 would be larger during the 20% V_{Dec} sled trials. The findings will allow coaches to
83 understand the impact of different loading strategies and more accurately prescribe
84 ST for the early acceleration phase.

85

86 **METHODS**

87

88 **Experimental Approach to the Problem**

89 This study used a randomised cross-over design to compare the effects of different
90 ST loadings and uninhibited sprinting. Twelve rugby league athletes performed a
91 series of 6 m sprints in four different conditions (Uninhibited, 10, 15 and 20% V_{Dec}).
92 The key dependant variables were the sagittal plane kinematic measures of the lower
93 extremities and trunk, the kinetic data obtained from the force platform and various
94 contact time measures.

95

96 **Subjects**

97 Twelve rugby league athletes from an elite academy (age: $18.9 \pm .6$ years; total body
98 mass: 90.2 ± 10.0 kg; stature: 1.80 ± 0.06 m) participated in this study. All subjects
99 were resistance trained (≥ 3 years) with ST experience and provided informed consent
100 before attending the testing sessions. The Institutional Ethics Committee in

101 accordance with the principles of the Declaration of Helsinki approved the testing
102 procedures implemented in this study. No external funding was provided for this study.

103

104 **Procedures**

105 One week prior to testing, all subjects completed a familiarization session. The same
106 sled was used throughout testing. The sled was attached to the subjects using a 3 m
107 non-elasticated attachment cord and waist belt (See Figure 1). Using a 6 m uninhibited
108 sprint as a baseline, sleds loadings (10, 15 and 20%) were determined in a random
109 order. Sprint times were recorded using infrared timing lights (Smartspeed Ltd.,
110 Fusionsports, Queensland, Australia) and sled loadings were adjusted to reduce 6 m
111 average velocity by the appropriate percentages (3). Mean sled loadings (sled plus
112 additional load) based on % V_{Dec} and the equivalent % BM values are shown in table
113 1.

114

115

116 @@@ Figure 1 inserted near here @@@

117

118 @@@ Table 1 inserted near here @@@

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120

121 Measures were taken to ensure that no force plate targeting occurred. Firstly, the
122 familiarization session was used to determine an individual starting position for each
123 subject. Starting positions were adjusted so that each participant's right foot
124 (dominant) contacted the force plate on their third step. Starting positions of the ST
125 trials were also adjusted accordingly and practiced until participants could consistently

126 land on the force plate. In order to standardise starting positions, trials began in a 3
127 point position. All participants chose to start with their left foot leading in the 3 point
128 starting position. Regardless of the starting point, subjects sprinted a total distance of
129 6 m.

130

131 Subjects were asked not to participate in any physical activity 24 hours before the
132 testing session. The testing session began with a standardised warm-up consisting of
133 jogging (5 min), dynamic stretching (5 min) and a number of short sprints building up
134 to maximum intensity (4 x submaximal and 2 x maximal).

135

136 Previous research has shown that ST trials can impact on the kinematics of any
137 subsequent uninhibited sprint trials (18). As such, the uninhibited sprint trials were
138 completed before any of the sled trials (10%, 15% and 20% V_{Dec}). Once the uninhibited
139 sprint trials were complete, all subsequent ST trials were randomized. Testing
140 procedures were identical to those described previously in the familiarisation section.
141 All subjects had 3 min recovery between each of the sprint trials. Five trials were
142 collected for each condition. Again, subjects sprinted a distance of 6m in a 22 m lab.
143 The surface friction coefficient (μ) of the lab ($\mu = 0.41$) was determined using methods
144 developed by Linthorne & Cooper (21). An embedded force platform, sampling at 1000
145 Hz, was positioned at approximately 3 m from the start (model 9281CA; dimensions =
146 0.6 x 0.4 m, Kistler Instruments Ltd). In order for the trials to be deemed successful,
147 the whole foot had to contact the force platform. Trials were discarded in cases where
148 any part of the foot did not land the force platform. Sprint times were generated for
149 every trial, and any trials in which sprint velocity deviated more than $\pm 5\%$ of the initial

150 trial in that condition were not used in the final analysis. In this instance, an extended
151 recovery period of 4 min was implemented and trials were repeated.

152

153 An eight camera motion analysis system (Qualisys Medical AB, Goteburg, Sweden)
154 was used to capture kinematic data at 250Hz. In order to determine stance leg
155 kinematics of the trunk, thigh, shank, and foot segments, retro-reflective markers were
156 placed on the following bony landmarks; the right calcaneus, 1st metatarsal head, 5th
157 metatarsal head, medial malleolus, lateral malleolus, medial epicondyle, lateral
158 epicondyle, acromion process (both), T12 and C7 (6). The trunk was tracked using
159 markers at both acromion processes, as well as the T12 marker. The pelvis segment
160 was defined, using additional markers on the anterior (ASIS) and posterior (PSIS)
161 superior iliac spines. Hip joint centre was determined based on the Bell et al. (2)
162 equations via the positions of the PSIS and ASIS markers. The ASIS, PSIS and greater
163 trochanters were used as tracking markers for the pelvis. Rigid cluster tracking
164 markers were also positioned on the right thigh and shank segments (5) Knee joint
165 centre was delineated as the mid-point between the femoral epicondyle markers. The
166 ankle joint centre was identified as the mid-point between the malleoli markers. During
167 dynamic trials the foot segment was tracked using the calcaneus, 1st and 5th metatarsal
168 heads. A static calibration was completed and used as reference for anatomical
169 marker placement in relation to the tracking markers, after which all non-tracking
170 markers were removed.

171

172 **Data Processing**

173 Motion files collected through the Qualisys track manager software and exported as
174 C3D files and quantified using Visual 3-D (C-Motion Inc., Germantown, USA) and

175 filtered with a cut-off frequency of 12Hz using a Butterworth 4th order filter to
176 adequately suppress motion artefacts without inducing excessive smoothing of the
177 traces (12,34). Three dimensional kinematics of the lower extremities and trunk were
178 calculated using an XYZ cardan sequence of rotations (X represents the sagittal plane,
179 Y represents the coronal plane and Z the transverse plane). The relevant segments
180 (thorax, thigh, shank and virtual foot) and reference segments (pelvis, thigh and shank)
181 were used to calculate joint angles of the trunk, hip, knee and ankle joints respectively.
182 The stance phase was determined as time over which 20N or greater of vertical force
183 was applied to the force platform (32). Kinematic waveforms were time-normalised to
184 100% of the stance phase and then all processed trials were averaged. Various
185 kinematic measures from the trunk, hip, knee and ankle joints were investigated: angle
186 at foot-strike, angle at toe-off, peak angle, range of movement (ROM) from foot-strike
187 to toe-off, and the relative ROM (the angular displacement from foot-strike to peak
188 angle) (Rel ROM). Resultant velocity at toe-off was calculated using the vertical and
189 horizontal centre of mass. These variables were extracted from each of the five trials
190 for each joint, data were then averaged within subjects for a comparative statistical
191 analysis.

192

193 Force plate data was collected through the Qualisys track manager software and
194 exported to Visual 3-D (C-Motion Inc., Germantown, USA) for processing. The
195 durations of the braking and propulsive phases were based on anterior and posterior
196 horizontal GRF. Peak GRF was determined for the following components: vertical,
197 braking, propulsive. Vertical impulse was calculated as the area under the vertical
198 ground reaction force-time curve (using a trapezoidal function) minus body weight
199 impulse over the time of ground contact. The braking and propulsive impulses were

200 determined by integrating all the negative and positive values of horizontal GRF,
201 respectively, over the time of ground contact (18,19). Net horizontal impulse was
202 calculated as propulsive impulse minus the absolute value of braking impulse. All
203 impulse measures were normalised to body mass so they represent changes in
204 velocity of centre of mass during ground contact (28). Similarly, mean values of vertical
205 and net horizontal GRF were obtained by dividing respective impulse values by the
206 contact time. Mean braking and propulsive GRF were calculated by dividing the
207 respective impulse values by the time duration of the braking and propulsive phases,
208 respectively (18). GRF measures were also normalised relative to body mass (3,18).

209

210 **Statistical Analysis**

211 Descriptive statistics were calculated and presented as mean \pm standard deviation
212 (SD). Dependant variables were examined using the uninhibited sprint trials. Test-
213 retest reliability and within-subject variation was evaluated using intraclass correlation
214 coefficient (ICCs) and coefficients of variance (CV%). Magnitudes of ICCs were
215 classified according to the following thresholds: 0.9 nearly perfect; 0.7–0.9 very large;
216 0.5–0.7 large; 0.3–0.5 moderate; and 0.1–0.3 small (15). One-way repeated measures
217 ANOVAs were used to compare the means of the different conditions (Uninhibited, 10,
218 15 and 20% V_{Dec}) with the different outcome measures (velocity, contact time, kinetics
219 and kinematics). Post hoc pairwise comparisons were conducted on all significant
220 main effects using a Bonferroni adjustment to control for type I error. Mauchly's test
221 was used to confirm sphericity for each analysis. If the assumption of sphericity was
222 violated, a Greenhouse-Geisser adjustment was used. Effect sizes were calculated
223 using partial eta² ($p\eta^2$), in accordance with Cohen (8) $p\eta^2 = 0.2$ considered small, $p\eta^2$

224 = 0.5 medium and $\eta^2 = 0.8$ large. Significance levels were set at $p \leq 0.05$. All statistical
225 analyses were undertaken using SPSS (Version 22, IBM SPSS Inc., Chicago, USA).

226

227 **RESULTS**

228

229 **Reliability of Measurement Variables**

230 Trials were monitored using sprint velocity which was shown to be reliable and have
231 little variation across the population ($ICCs \geq 0.9$; $CV\% = 1.6$). Range of ICCs and CV%
232 between participants and trials varied greatly among the other measurement variables
233 (ranges shown after each section).

234

235 Figure 2 presents the mean sagittal plane angular kinematics during the stance phase.

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237

238 @@@ Figure 2 inserted near here @@@

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240

241 **Velocity and Contact Time Measures**

242 Table 2 presents the stance phase contact time and velocity data. Velocity was
243 reduced significantly in all sled conditions as loading increased ($p = 0.001$). Contact
244 times increased significantly in all sled conditions as loading increased ($p < 0.001$). All
245 sled conditions resulted in significantly greater propulsive times than uninhibited
246 sprinting ($p < 0.001$), propulsive times increased with loading ($p < 0.05$). ICCs ranging
247 between .47 (brake time) and .90 (velocity) were calculated. CV% ranging between
248 1.6 (velocity) and 28.8% (brake time) were calculated.

249

250

251

@@@ Table 2 inserted near here @@@

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253

254 **Kinetic Measures**

255 The kinetic variables can be observed in Table 3. Vertical mean force during the 20%

256 loading condition was significantly lower than the uninhibited trials ($p = 0.024$). Net

257 horizontal mean force was greater in all ST conditions compared to the uninhibited

258 trials ($p < 0.01$). There was no significant difference between ST conditions ($p > 0.05$).

259 The propulsive mean force recorded during the 20% loading was significantly higher

260 than that of the uninhibited condition ($p = 0.032$). Again, there was no significant

261 difference between ST conditions ($p > 0.05$). Net horizontal and propulsive impulse

262 measures were significantly greater as sled loading increased ($p < 0.05$). ICCs ranging

263 between .22 (net horizontal impulse) and .66 (braking peak force) were calculated.

264 CV% ranging between 6.9 (propulsive peak force) and 67.6% (braking mean force)

265 were calculated.

266

267

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269

@@@ Table 3 inserted near here @@@

270

271

272 **Trunk Kinematics**

273 The results (see Table 4) indicate that trunk angle at toe-off was significantly greater
274 during ST than the uninhibited trials ($p < 0.05$). There was no significant difference
275 between ST conditions ($p > 0.05$). Relative trunk ROM was significantly greater in the
276 20% loading condition compared to the uninhibited trials ($p = 0.035$). ICCs ranging
277 between .68 (Rel ROM) and .94 (angle at foot-strike) were calculated. CV% ranging
278 between 7.4 (Rel ROM) and 16.1% (ROM) were calculated.

279

280

281 @@@ Table 4 inserted near here @@@

282

283

284 **Hip Joint Kinematics**

285 Hip joint measures can be observed in Table 5. ST had no significant impact on
286 kinematics of the hip joint. ICCs ranging between .88 (peak flexion) and .94 (angle at
287 toe-off) were calculated. CV% ranging between 4.9 (peak flexion) and 30.7% (angle
288 at toe-off) were calculated.

289

290

291 @@@ Table 5 inserted near here @@@

292

293

294 **Knee Joint Kinematics**

295 Knee joint measures can be observed in Table 5. Knee flexion at foot-strike was
296 significantly greater as sled loading increased ($p < 0.05$). Similarly, peak flexion was
297 greater as loading increased ($p < 0.05$). ROM in all ST conditions were significantly

298 greater than the uninhibited trials ($p < 0.01$). ROM in the 20% sled loading condition
299 was also significantly greater than the 10% condition ($p = 0.001$). ICCs ranging
300 between .63 (Rel ROM) and .82 (angle at toe-off) were calculated. CV% ranging
301 between 5.1 (peak flexion) and 20.1% (ROM) were calculated.

302

303

304 @@@ Table 6 inserted near here @@@

305

306

307 **Ankle Kinematics**

308 The results (see Table 7) indicate that ankle ROM during ST conditions were
309 significantly greater than the uninhibited trials ($p < 0.05$). There was no significant
310 difference between ST conditions ($p > 0.05$). ICCs ranging between .70 (angle at foot-
311 strike) and .94 (angle at toe-off) were calculated. CV% ranging between 7.4 (angle at
312 toe-off) and 21.0% (angle at foot-strike) were calculated.

313

314

315 @@@ Table 7 inserted near here @@@

316

317

318 **DISCUSSION**

319

320 To our knowledge, this is the first ST study to examine trunk and lower body
321 kinematics, contact time variables and kinetics during early acceleration in high-level
322 field sport athletes. Therefore, this study will provide a valuable insight for strength

323 and conditioning coaches looking to prescribe ST (% V_{Dec}) for field sport athletes. The
324 major findings of this study were (a) as sled loadings increased trunk and lower
325 extremity kinematics were altered to a greater extent, (b) there were no significant
326 differences in propulsive peak force between any of the sled conditions and uninhibited
327 sprinting, and (c) propulsive impulse measures in the 20% V_{Dec} sled trials were
328 significantly greater than all other conditions.

329

330 In general, sprint kinematics were affected in all sled conditions when compared with
331 uninhibited sprinting. This supports previous research (3,18) and casts further doubt
332 on the belief that lighter sled loadings (10% BM or 10% V_{Dec}) will not affect sprint
333 kinematics. Previous investigations have suggested that when heavier sleds are
334 utilised kinematic alterations to stride length and frequency are greater (22,24,30).
335 Although stride length and frequency were not measured in the present study, our
336 results indicate that velocity and contact time were affected to a greater extent when
337 sled loadings were increased. The longer contact times were explained by an
338 extended propulsive phase, as suggested previously (18,25,30). The additional
339 contact time allows the athlete to exert greater propulsive forces to overcome the extra
340 resistance provided by the sled. This increased propulsive contact time may be
341 beneficial for acceleration performance, in this instance more horizontal force can be
342 applied to the ground (19,27).

343

344 ST with light to moderate loadings using a waist harness attachment appears to have
345 no significant impact on hip joint kinematics. This finding differs from previous research
346 by Monte et al. (25) who reported significant kinematic alterations at the hip, knee and
347 ankle joints at foot-contact and take-off. However, the greater sled loadings utilised in

348 their study (30 and 40% BM) likely explains the difference. The only kinematic
349 alterations observed at the ankle joint in the present study was a significantly lower
350 ROM in the uninhibited condition compared to all ST trials. The change in ROM during
351 sled trials was explained by a trend of increased dorsiflexion at foot-strike and
352 increased plantarflexion at toe-off. Kinematic adjustments of this nature appear to
353 allow the athletes to increase their stance phase contact times, as discussed
354 previously. Our results show that there were a number of significant kinematic changes
355 at the knee joint. Knee flexion at foot-strike and peak flexion were greater in all sled
356 conditions and increased in line with loading. We believe these adjustments allow the
357 athletes to lower their centre of mass and increase contact time, thus helping them
358 overcome the added resistance of the sled by increasing their horizontal force
359 application. Studies have highlighted the importance of trunk kinematics during ST
360 and uninhibited sprinting alike (3,19). Our results support this finding; extension of the
361 trunk was significantly greater in the uninhibited condition compared to all sled
362 conditions at toe-off. There was a trend for greater trunk flexion as sled loadings
363 increased; however, this was not significant. Along with increased peak knee flexion,
364 the authors believe the increased trunk flexion at toe-off enables the athlete to
365 increase their horizontal force application. Adaptations of this nature have been
366 reported after sled towing interventions, during acceleration such practice effects may
367 lead to greater propulsive forces in the later stance phase (1,19,35).

368

369 The authors hypothesised that propulsive peak force would be greatest in the 20%
370 V_{Dec} sled condition. Results did not support this; there was however, a trend that as
371 sled loading increased so too did propulsive peak force. It does appear that propulsive
372 peak force would continue to increase with heavier sled loadings, as suggested in

373 previous studies (27). It is important to note that such increases are at the expense of
374 much greater contact times, which after a certain point may become counterproductive
375 (24). Additionally, previous research suggests that the magnitude of forces may not
376 be as important as the direction of force application (19,26). Propulsive mean force
377 was significantly higher and vertical mean force significantly lower in the 20% V_{Dec} sled
378 condition. These kinetic changes again highlight the increased horizontal force vector
379 orientation when towing moderate sled loads.

380

381 Net horizontal and propulsive impulses are key determinants of early acceleration
382 (16,19). However, simply maximising these measures at the expense of other key
383 variables such as contact times may not be beneficial (19). Our results indicate that
384 both net horizontal and propulsive impulses were significantly greater in all sled
385 conditions and increased in line with sled loading. This supports the findings of
386 previous investigations that utilised similar sled loading strategies (18). Again, the
387 larger impulse measures reported can be explained by the increased contact times.
388 As such, when rapid acceleration and shorter contact times are a priority 20% V_{Dec}
389 sled towing may not be the ideal loading strategy, during these specific pre-
390 competition training periods uninhibited sprinting might be more appropriate. However,
391 during the general preparation phase of training coaches may look to overload
392 horizontal force application with this loading strategy. In this instance, ST may
393 enhance the transition between high-strength and high-velocity exercises (1).

394

395 Unsurprisingly, heavier sled loadings led to a greater sprint velocity reduction (31). In
396 the present study sled loadings were determined using % V_{Dec} rather than % BM. Sled
397 loadings adjusted based on % BM will not provide an optimal overload among all

398 athletes because this method does not account for the athlete's muscular strength and
399 sprint technique (18). Greater individual differences were apparent when towing
400 heavier sleds, highlighted in this investigation by larger standard deviations as sled
401 loadings increased. As such, it is recommended that coaches load sleds based on a
402 % V_{Dec} rather than a % BM.

403

404 Investigations have demonstrated that females exhibit distinct lower body kinematics
405 when compared with males (33). As such, the results are limited to this population and
406 may not be applicable to female athletes. Similarly, the results are specific to the highly
407 trained population and may not be applicable to recreational athletes. The light to
408 moderate sled loadings utilised in this study may be a limitation. Researchers have
409 recently suggested that very heavy sled loadings may provide the optimal training
410 stimulus by maximising peak power output (11). It is beyond the scope of the present
411 study to comment on such loading strategies.

412

413 **Practical Applications**

414 Overall, the results of this study have shown that a sled loading of 20% V_{Dec} enables
415 coaches to increase propulsive forces and impulses. However, a blanket application
416 of such loads may not be the most appropriate strategy as some of the acute changes
417 are potentially counterproductive, such as reduced velocity and greatly increased
418 contact times. Thus, perhaps a periodized approach should be adopted. For example,
419 training with a 20% V_{Dec} sled loading will allow a greater emphasis on the horizontal
420 application of forces then progressing to lighter sled loads or uninhibited sprint training
421 to allow greater transfer of potential adaptations (e.g., maintain force/ impulse
422 production whilst lowering contact times). The study therefore, highlights the effects of

423 differential loads to help coaches understand acute biomechanical changes in order
424 to improve planning of sprint training.

425

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546 **Figure labels**

547 Figure 1. The sled, cord and harness attachment.

548 Figure 2. Mean trunk (a) hip (b) knee (c) and ankle (d) joint angles in the sagittal
549 plane for the uninhibited (bold black line), 10% (bold grey line), 15% (dashed black
550 line) and 20% (dotted grey line) conditions.

551

552 Table 1 – Sled Loadings by percent of V_{Dec} (means and standard deviations)

553

Loading Strategy	10%	15%	20%
% V _{Dec} (kg)	11.6 ± 2.3	17 ± 4.4	22.9 ± 5.6
Equivalent % BM	12.8 ± 2.1	18.8 ± 3.9	25.4 ± 5.3

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555

556 Table 2 – Velocity and Contact time measures (means and standard deviations) under the different
 557 conditions (uninhibited, 10%, 15% and 20% V_{Dec})

558

	Uninhibited	10%	15%	20%	Main Effect	$p\eta^2$
Velocity (m/s)	5.49 ± .25**	4.94 ± .26**	4.69 ± .26**	4.44 ± .29**	†	.95
Contact time (s)	.17 ± .01**	.19 ± .01**	.20 ± .01**	.21 ± .01**	†	.81
Brake time (s)	.02 ± .01	.02 ± .01	.01 ± .01	.01 ± .01		.12
Propulsive time (s)	.15 ± .01**	.17 ± .01**	.19 ± .01**	.20 ± .02**	†	.77

559 ** Significantly different from all other conditions $p \leq 0.05$

560 † highlights a significant main effect $p \leq 0.05$

561

562

563 Table 3 – Kinetic measures (means and standard deviations) under the different conditions
 564 (uninhibited, 10%, 15% and 20% V_{Dec})

565

	Uninhibited	10%	15%	20%	Main Effect	η^2
Vertical peak force (N.kg ⁻¹)	9.53 ± 1.69	8.01 ± 1.80	8.33 ± 2.01	8.26 ± 1.87	†	.26
Vertical mean force (N.kg ⁻¹)	2.94 ± .94	2.19 ± 1.07	2.23 ± 1.19	2.03 ± .87*	†	.35
Vertical impulse (m.s ⁻¹)	.51 ± .16	.42 ± .21	.45 ± .24	.43 ± .20		.12
Net horizontal mean force (N.kg ⁻¹)	3.39 ± .27**	3.71 ± .26	3.83 ± .30	3.94 ± .36	†	.67
Net horizontal impulse (m.s ⁻¹)	.58 ± .03**	.71 ± .04**	.76 ± .05**	.83 ± .09**	†	.85
Braking peak force (N.kg ⁻¹)	3.09 ± 1.72	2.53 ± 1.50	2.19 ± 1.35	2.08 ± 1.23	†	.33
Braking mean force (N.kg ⁻¹)	1.43 ± 1.04	1.00 ± .78	.93 ± .70	.85 ± .63		.16
Braking impulse (m.s ⁻¹)	.02 ± .02	.01 ± .02	.01 ± .01	.01 ± .01		.11
Propulsive peak force (N.kg ⁻¹)	6.73 ± .42	6.84 ± .50	6.92 ± .58	7.00 ± .57	†	.21
Propulsive mean force (N.kg ⁻¹)	3.93 ± .29	4.17 ± .28	4.21 ± .40	4.31 ± .45*	†	.39
Propulsive impulse (m.s ⁻¹)	.61 ± .03**	.72 ± .05**	.77 ± .05**	.84 ± .09**	†	.86

566 * Significantly different from uninhibited sprinting $p \leq 0.05$

567 ** Significantly different from all other conditions $p \leq 0.05$

568 † highlights a significant main effect $p \leq 0.05$

569

570

571 Table 4 – Trunk kinematics (means and standard deviations) under the different conditions
 572 (uninhibited, 10%, 15% and 20% V_{Dec})

573

X (+=flexion/=-extension)	Uninhibited	10%	15%	20%	Main Effect	pη ²
Angle at foot-strike (°)	6.5 ± 7.3	8.0 ± 8.7	8.1 ± 8.2	9.0 ± 9.8		.07
Angle at toe-off (°)	-6.6 ± 7.6**	-1.0 ± 9.1	-.1 ± 8.7	2.5 ± 10.4	†	.44
Peak flexion (°)	7.2 ± 6.9	9.4 ± 8.8	9.6 ± 8.3	11.5 ± 9.7		.16
ROM (°)	13.1 ± 6.6	9.0 ± 4.7	8.2 ± 3.1	7.2 ± 3.2	†	.35
Rel ROM (°)	.7 ± 1.4	1.3 ± 1.5	1.5 ± 1.6	2.4 ± 2.0*	†	.39

574 * Significantly different from uninhibited sprinting p ≤ 0.05

575 ** Significantly different from all other conditions p ≤ 0.05

576 † highlights a significant main effect p ≤ 0.05

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578

579 Table 5 – Hip kinematics (means and standard deviations) under the different conditions (uninhibited,
 580 10%, 15% and 20% V_{Dec})

581

X (+=flexion/=-extension)	Uninhibited	10%	15%	20%	Main Effect	pη ²
Angle at foot-strike (°)	64.9 ± 8.4	68.1 ± 7.9	69.9 ± 7.7	71.1 ± 9.8	†	.30
Angle at toe-off (°)	3.4 ± 9.0	5.2 ± 10.7	5.7 ± 10.3	5.2 ± 11.3		.07
Peak flexion (°)	64.9 ± 8.4	68.1 ± 7.9	69.9 ± 7.7	71.1 ± 9.8	†	.30
ROM (°)	61.4 ± 9.2	62.9 ± 7.4	64.2 ± 6.5	65.9 ± 8.0		.20

582 † highlights a significant main effect p ≤ 0.05

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584

585 Table 6 – Knee kinematics (means and standard deviations) under the different conditions
 586 (uninhibited, 10%, 15% and 20% V_{Dec})

587

X (+=flexion/- =extension)	Uninhibited	10%	15%	20%	Main Effect	pn ²
Angle at foot-strike (°)	50.7 ± 5.4**	55.0 ± 6.5**	57.8 ± 5.6**	60.8 ± 7.2**	†	.75
Angle at toe-off (°)	21.0 ± 5.0	21.1 ± 4.3	21.8 ± 5.2	22.4 ± 4.9		.12
Peak flexion (°)	52.0 ± 5.4**	56.0 ± 6.0**	58.6 ± 4.9**	61.7 ± 6.5**	†	.77
ROM (°)	29.8 ± 6.7**	33.9 ± 8.1§	36.1 ± 7.7	39.3 ± 7.4	†	.73
Rel ROM (°)	1.3 ± 1.9	1.0 ± 1.7	.8 ± 1.5	.9 ± 2.8		.02

588 § Significantly different from 20% loading p ≤ 0.05

589 ** Significantly different from all other conditions p ≤ 0.05

590 † highlights a significant main effect p ≤ 0.05

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592

593 Table 7 – Ankle kinematics (means and standard deviations) under the different conditions
 594 (uninhibited, 10%, 15% and 20% V_{Dec})

595

X (+=dorsiflexion/ -plantarflexion)	Uninhibited	10%	15%	20%	Main Effect	pη ²
Angle at foot-strike (°)	4.3 ± 3.7	5.1 ± 3.3	5.1 ± 3.8	6.2 ± 3.8		.18
Angle at toe-off (°)	-24.1 ± 6.2	-25.3 ± 6.1	-25.8 ± 6.9	-25.8 ± 7.1	†	.28
Peak dorsiflexion (°)	23.6 ± 4.0	24.1 ± 4.2	24.3 ± 4.7	25.0 ± 5.1		.10
ROM (°)	28.4 ± 5.3**	30.4 ± 5.6	31.0 ± 6.5	32.0 ± 5.8	†	.50
Rel ROM (°)	19.4 ± 2.8	19.0 ± 3.2	19.2 ± 3.8	18.8 ± 2.7		.04

596 ** Significantly different from all other conditions p ≤ 0.05

597 † highlights a significant main effect p ≤ 0.05

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