

Variability of plyometric and ballistic exercise technique maintains jump performance

ABSTRACT

The aim of this study was to investigate changes in vertical jump technique over the course of a training session. Twelve plyometric and ballistic exercise trained male athletes (age = 23.4 ± 4.6 years, body mass = 78.7 ± 18.8 kg, height = 177.1 ± 9.0 cm) performed three sets of 10 repetitions of drop (DJ), rebound (RJ) and squat jumps (SJ). Each exercise was analysed from touch down to peak joint flexion and peak joint flexion to take-off. SJ were analysed from peak joint flexion to take-off only. Jump height, flexion and extension time and range of motion, and instantaneous angles of the ankle, knee and hip joints were measured. Separate one-way repeated ANOVAs compared vertical jump technique across exercise sets and repetitions. Exercise set analysis found SJ had lower results than DJ and RJ for the angle at peak joint flexion for the hip, knee and ankle joints and take-off angle of the hip joint. Exercise repetition analysis found the ankle joint had variable differences for the angle at take-off, flexion and extension time for RJ. The knee joint had variable differences for flexion time for DJ and angle at take-off and touch down for RJ. There was no difference in jump height. Variation in measured parameters across repetitions highlights variable technique across plyometric and ballistic exercises. This did not affect jump performance, but likely maintained jump performance by overcoming constraints (e.g. level of rate coding).

INTRODUCTION

Plyometric and ballistic exercises are common place in athletic training for many sports to improve vertical jump performance. Plyometric exercise refers to the use of the stretch-shortening cycle, where a high-intensity eccentric contraction occurs immediately before a rapid concentric contraction (18). Plyometric exercises usually involve

24 various types of body weight jumping, such as drop jumps (DJ) and countermovement jumps (CMJ). Ballistic
25 exercise is defined by the explosive release of the body into the air, but the overall duration of the exercise is
26 longer mainly due to an extended ground contact time, such as a squat jump (SJ).

27
28 Numerous studies have found improvement in vertical jump performance after a period of vertical jump training
29 incorporating both ballistic and plyometric exercises. A meaningful improvement of 4.8 cm have been found in
30 CMJ height after six weeks of vertical jump training in basketball athletes (19). Further significant improvements
31 of 13.2% have been found in CMJ height after six weeks of additional vertical jump exercise in athletic training
32 (24). Periods of plyometric training have also been found to increase vertical jump height in both male (7) and
33 female athletes (22), thus justifying its inclusion in athletic training to improve jump performance in all athletic
34 populations.

35
36 Plyometric and ballistic exercise technique has been extensively researched to find methods of improving jump
37 performance (8, 20, 25, 26). Jump height is considered the main performance output of a ballistic and plyometric
38 exercise, therefore is extensively measured by strength and conditioning coaches to identify the best jump
39 technique. A Greater squat depth is argued to produce a greater jump height in a SJ (8, 20). A greater net impulse
40 was found with greater squat depth (8), due to greater amount of time taken to execute the jump, which may cause
41 the greater jump height. Although, a CMJ has found to have a greater jumper height than a SJ, and further had a
42 greater impulse during smaller squat depths (20). Thus, opposite of SJ, a greater force is produced relative to time
43 in a CMJ with less of a squat depth creating a greater jump height.

44
45 The literature suggests several methods for increases in jump height caused by better jump technique, therefore
46 jump height alone does not identify how said jump is achieved. Measurement of kinetic parameters, such as peak
47 ground reaction force or impulse, would better identify vertical jump intensity, but would be influenced by range
48 of motion and jump timings during different phases (i.e. touchdown, peak joint flexion and take-off) of a ballistic

49 or plyometric jump. Knee and ankle flexion have found to increase after a CMJ fatigue protocol by 7.0° and 10.6°,
50 while vertical ground reaction force did not significantly differ (26). This highlights a change in jump technique
51 to maintain vertical ground reaction force, therefore optimal jump technique is influenced by kinematic measures.
52 Therefore, if the strength and conditioning coach monitored kinematic parameters, such as range of motion and
53 jump timings, it would provide insight into if and/or how the range of motion and timing of said range of motion
54 influence jump technique to achieve jump height (i.e. if a shallower but faster range of movement is achieved
55 then forces will likely be larger compared to a deeper but slower range of movement and if this impacts of jump
56 height).

57
58 Research agrees jump technique between each type of plyometric and ballistic exercise differs, however, all
59 research has looked at plyometric and ballistic exercise in isolation, where the strength and conditioning coach
60 will employ them in a training session. Therefore, it is not known if the jump technique will differ between
61 plyometric and ballistic exercise in a training session or between repetitions in the same exercise set. It is
62 important for the strength and conditioning coach as they will be able to identify the best jump technique to bring
63 about greater jump performances. Therefore, the aim of this study was to investigate kinematic changes of
64 plyometric and ballistic exercise technique over the course of a training session to identify the best jump
65 technique. It is hypothesized that as drop jump exercise produces the greatest jump height, will have to best jump
66 technique. Furthermore, jump height between exercise repetitions will decrease throughout the exercise set,
67 therefore the best jump technique will be at the start of the exercise set.

69 **METHOD**

70 **Experimental approach to the Problem**

71 Data for this study was collected from 12 athletes, experienced in plyometric and ballistic exercise training. Prior
72 to completing the study, all participants passed the NSCA recommendations for prerequisites of completing
73 plyometric exercise (2). This study was a cross sectional study design.

75 **Subjects**

76 Twelve male athletes (age = 23.4 ± 4.6 , body mass = 78.7 ± 18.8 kg, height = 177.1 ± 9.0 cm), experienced in
77 plyometric and ballistic exercise training and participated in lower body power sports (e.g. Judo, Javelin,
78 Sprinting), volunteered to participate in the study. All participants competed at club level, and testing was
79 complete in the off-season of each sport.

81 The study was approved by a University ethics board prior to starting. All participants received a clear explanation
82 of the study including the benefits and risks of the investigation prior to signing an institutionally approved
83 informed consent document to participate in the study. No funding or endorsements were used in this study

85 **Procedures**

86 All participants completed a familiarisation and a testing session separated by 72 hours. All sessions were
87 complete at the same time of day to allow for variations in strength gains due to training at different times of the
88 day (23). Participants were asked to refrain from any form of exercise 72 hours before testing. Participants were
89 further asked to maintain the same level of hydration and continue a regular eating pattern prior to each laboratory
90 visit.

92 Familiarisation and testing sessions were identical except no measurements were taken during the familiarisation
93 session. All sessions involved the same plyometric exercises; DJ, rebound jump (RJ) and SJ. The DJ involved
94 participants dropping off a 40 cm high box leading with their dominant leg. Dominant leg was determined by
95 asking the participant. The 40 cm drop height was selected as it is reportedly in the range of optimal dropping

96 height (40-60 cm), measured in 19 young participants (1). The RJ involved repetitive CMJ to a self-selected depth,
97 initiated by a CMJ. The first jump was not analysed due to it not been a true rebound jump, as a jump did not
98 precede it. The SJ involved a countermovement to a self-selected depth to initiate the beginning of the jump, but
99 participants were instructed to hold for three seconds at the bottom of the countermovement before completing a
100 maximal jump. If the position was not held at the bottom of the countermovement for three seconds, the jump
101 was discounted and completed again.

102
103 During the DJ and RJ all participants were instructed to jump as high and as fast as possible with minimum ground
104 contact, whereas for the SJ participants were instructed to jump as high as possible. All jumps were completed
105 with arm swing to reflect a true training session and achieve maximal height.

106
107 All sessions started with a warm up, consisting of 10 minutes cycling at 100 W, followed by 10 minutes of
108 dynamic stretches. The participants then completed three submaximal repetitions of each plyometric and ballistic
109 exercise with two minutes rest in between. This allowed for the experimenter, an accredited strength and
110 conditioning coach, to assess appropriate technique. Appropriate technique for all exercises included bilateral
111 landing, with stable ankle, knee and hip joints, with no forward trunk lean.

112
113 The familiarisation and testing session consisted of three sets of 10 repetitions of DJ, RJ and SJ, completed in that
114 order to represent a typical training session. Three minutes of rest between sets was allowed to meet
115 recommendations of an optimal work to rest ratio of 1:5 to 1:10 (2). The number of foot contacts, 120, matched
116 recommendations for intermediate athletes as all athletes had experience of plyometric and ballistic exercises in
117 their own training and sport (2).

118
119 All exercises were completed on a force plate (Bertec, Columbus, U.S.A). The force plate was used to determine
120 parameters mentioned later in this methodology. 10 mm spherical markers were attached to the fifth metatarsal,

121 lateral malleoli, knee, greater trochanter and shoulder on the dominant side of all participants. Placement of
122 markers has been used in previous research (12). The markers were tracked using a 6-camera three-dimensional
123 (3D) motion capture system (Proreflex, Qualisys, Savadalen, Sweden) to identify bony landmarks.

124
125 Motion analysis software (Qualisys track manager, Qualisys, Savadalen, Sweden) was used to measure ankle,
126 knee and hip angles at touch down, peak joint flexion and take-off for DJ and RJ. Touch down was determined
127 by the point when the right foot first touched the ground, shown by a force greater than 20 N on the force plate.
128 Peak joint flexion was determined by maximum knee flexion, while take-off was determined by the last contact
129 of the right foot on the ground, shown by a force less than 20 N on the force plate.

130
131 Ankle, knee and hip angles at first movement, peak joint flexion and take-off were measured for the SJ. First
132 movement was determined by an increase in force by 20 N on the force plate. Peak joint flexion and take-off for
133 SJ were determined in the same manner for DJ and RJ.

134
135 Flexion and extension range were calculated for DJ and RJ from the difference between angle at touch down and
136 peak joint flexion, and the difference between angle at the peak joint flexion and take-off, respectively. Flexion
137 and extension time for DJ and RJ were determined by the time difference of the same movements mentioned for
138 flexion and extension range. Flexion and extension range were calculated for SJ from the difference between
139 angle at first movement and peak joint flexion, and the difference between angle at the peak joint flexion and
140 take-off, respectively. Flexion and extension time for SJ were determined by time difference for the same
141 movements mentioned for flexion and extension range. Jump height was measured by the greatest displacement
142 of the greater trochanter reflective marker relative to take-off.

144 **Statistical analyses**

145 Statistical analysis was completed on sets of plyometric and ballistic exercises (exercise sets) and repetitions of
146 plyometric and ballistic exercises (exercise repetitions) to determine differences between vertical jump exercise
147 sets and repetitions. Exercise sets were calculated by the mean scores for each vertical jump exercise set. Exercise
148 repetitions were calculated by the mean of each repetition of vertical jump exercise.

149
150 Initial testing of normality and homogeneity of variance of data was completed to determine the use of a
151 parametric or none parametric tests. For data that passed these tests, separate one-way repeated ANOVA tests
152 were complete to determine differences between vertical jump exercise sets and exercise repetitions. Where
153 significant differences were detected a paired samples t-test was used to determine the differences.

154
155 If the test of normality or homogeneity of variance was not met, a non-parametric equivalent test was complete.
156 In this case, the Freidman's test determined any differences between vertical jump exercise sets and exercise
157 repetitions. Where significance was found, a Wilcoxon's signed rank test was completed with manual Bonferroni
158 adjustments to determine the differences. Significance for all tests was set at $p < .05$.

159
160 Cohen's d effect size (ES) was used to calculate practically meaningful differences among all measured
161 parameters. ESs of <0.2 , $0.2-0.6$, $0.61-1.2$ and >1.2 were considered trivial, small, moderate and large,
162 respectively (3). Infraclass correlations coefficients (ICC) were calculated of each exercise for each kinematic
163 parameter to determine reliability of each kinematic measurement. The ICC classifications of Fleiss (less than
164 0.4 was poor, between 0.4 and 0.75 was fair to good, and greater than 0.75 is excellent) were used to describe the
165 range of ICC values (10). All statistical analyses were performed in SPSS (version 22.0, SPSS Science Inc,
166 Chicago, IL, USA).

167 168 **RESULTS**

170 ICC results show kinematic measures of plyometric and ballistics exercises to be reliable (Table 1). Results of
171 exercise sets analysis showed significant differences between all kinematic parameters. Post hoc analysis of
172 exercise set results are shown in Tables 2, 3 and 4.

173 Insert table 1 about here

174 Insert table 2 about here

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177 Results of the analysis of exercise repetitions for the knee joint showed significant differences between repetitions
178 for DJ flexion time ($P = 0.01$, $ES = 0.84 - 0.58$). The repetition significant difference for DJ knee flexion time is
179 shown in Figure 1. RJ knee joint angle at touch down ($P = 0.03$, $ES = 1.10 - 0.66$), angle at take-off ($P = 0.03$, ES
180 $= 0.78 - 0.58$) and flexion time ($P = 0.04$, $ES = 0.72 - 0.84$) found significant difference between repetitions. The
181 repetition significant differences for the knee joint of the RJ are shown in Figure 2. SJ angle at touch down ($P =$
182 0.01 , $ES = 0.78 - 0.55$) and extension range ($P = 0.01$, $ES = 0.84 - 0.55$) found significant differences between
183 repetitions for the knee. The significant repetition differences of the knee joint for the SJ are shown in Figure 3.
184 Significant differences of the ankle joint between repetitions were found for DJ angle at touch down ($P = 0.03$,
185 $ES = 0.89 - 0.72$), with significant differences shown in Figure 4. RJ ankle angle at take-off ($P = 0.03$, $ES = 0.81$
186 $- 0.66$), flexion time ($P = 0.01$, $ES = 0.81 - 0.58$) and extension time ($P = 0.05$, $ES = 0.81 - 0.58$) found significant
187 difference between repetitions. The significant differences between repetitions are shown in Figure 5. Significant
188 differences of the hip joint between repetitions were only found for SJ angle at touch down ($P = 0.01$, $ES = 0.89$
189 $- 0.58$). The significant difference between repetitions are shown in Figure 6.

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DISCUSSION

This is the first study to investigate plyometric and ballistic exercise technique via kinematic measures over the course of a training session to identify optimal jump technique. This study found kinematic measures of vertical jump exercises to be reliable, with all kinematic parameters being classed as excellent except for touch down, flexion range and extension time for SJ being classed as fair to good. This agrees with Malfait et al. (2014) finding a 3.2° to 3.5° variability in lower limb joint angles between a series of DJ, leading to the authors reporting DJ kinematic data to be reliable (17). Ford et al. (2007) is in further agreement finding ICCs ranging from 0.933 to 0.993 for lower limb joint angles measured during drop jumps (11). These studies support the present study's findings of kinematic data being a reliable measure of plyometric and ballistic jump technique, therefore it can be suggested that each kinematic variables are consistent and accurate and may be used to measure optimal vertical jump technique.

Analysis of exercise sets found SJ to be significantly different from DJ and RJ for several kinematic variables across all joints. Similar results have been reported in previous research, finding differences between flexion angles and angles at take-off for the hip, knee and ankle joints between CMJ and SJ (16). This highlights that there are different techniques utilized between vertical jump exercises. Therefore, the strength and conditioning coach should be aware of different techniques as this may influence the technical aspect of training a vertical jump exercise.

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217 The present study found DJ jump height to be lower than RJ and SJ. This is not consistent with previous literature
218 with numerous studies finding DJ and RJ to have a greater jump height than SJ. Previous research found a 23 cm
219 difference between DJ and SJ (12), and an average of 2.4 cm difference between CMJ and SJ (4). This was
220 attributed to agonist muscles having greater time to develop more cross-bridge attachments during muscle
221 contraction. This led to greater moments at the hip, knee and plantarflexion leading to greater force production
222 (4). Greater electromyography activity in active muscles during a CMJ has been found, which was attributed to
223 greater muscle activation and elastic recoil (9). Further suggested mechanisms involve a pre-stretch created by
224 the countermovement in DJ and RJ led to storage of energy in the serial elastic elements, which was later utilized
225 when muscles act concentrically to increase jump height (13). The literature suggests numerous reasons for the
226 greater jump height in DJ and RJ. It would be reasonable to suggest that not one mechanism is the cause of the
227 greater jump height, but a combination of all mechanisms.

228

229 Although, Kotzamanidis et al. (2005) is in agreement with the present study finding DJ to have the lowest jump
230 height of 20.07 cm, compared to SJ and RJ with jump heights of 25.51 cm and 27.83 cm, respectively (14). This
231 may be due to a longer pre-stretch time leading to less energy transferred to the series elastic element, causing a
232 lower net impulse, for further utilization. Participants not been able to attenuate the large impact forces on initial
233 landing may cause the longer pre-stretch time where less force is transferred to the propulsive phase of the jump.
234 Therefore, use of a lower drop height for DJ may benefit some athletes that cannot attenuate impact forces from
235 larger drop heights. Ground reaction forces can be used to monitor attenuation of impact forces to help the strength
236 and conditioning coach progress drop heights for DJ exercises.

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238 Results of exercise repetition analysis show variability between kinematic parameters. For example, during the
239 RJ exercise, the knee angle at touch down for repetition 10 of set 1 is significantly different to repetition 4, 7 and

240 9 of the same set, but repetition 10 of set two has no significant difference to any other repetitions. This highlights
241 variation in vertical jump technique throughout the course of the training session. Similar variability was found
242 when investigating basketball free throw technique (5). The authors found variability in wrist and elbow angle to
243 adapt to constraints in release parameters of the ball (5). The variability of technique were made to maintain
244 shooting accuracy, therefore shooting technique changed to maintain performance.

245
246 Davids et al. explained constraints to be boundaries that interact to limit the optimal movement state (6).
247 Constraints are characterised in to three groups. Individual where constraints are located inside the body. External
248 when constraints are in the environment and task where constraints are related to a skill or specific task (6). Latash
249 et al. argued that the body will adapt its output to compensate for the constraints imposed upon it, so that
250 movement is maintained as close to optimal as possible (15). Therefore, in the present study, the jump technique
251 variability is likely reflective of the body compensating for the constraints experienced. As no significant
252 difference was found between vertical jump exercise repetitions and jump height, it is argued that the jump
253 technique variability maintains jump performance.

254
255 The amount of technique variation differed between vertical jump exercises as DJ only experienced variation at
256 the knee joint, while RJ and SJ elicited variation at the hip, knee and ankle joints. This may be due to the level of
257 experience of a task. Comparison of expert and novice marksmen during a pistol target shooting task found experts
258 to have different angles at the shoulder and elbow but not the wrist during target shooting (21). However, novices
259 had variability at the wrist joints only (21). The authors suggested the experts were able to employ a flexible
260 degrees of freedom, (21). Degrees of freedom are the numerous independent ways an athlete can move (6),
261 therefore, experts employed a different degree of freedom to each individual target shot depending on the
262 constraints imposed upon them. The novices could not and used a more rigid degrees of freedom approach. This
263 phenomenon is known as functional variability allowing experts to use variable technique to maintain

264 performance (6). In the present study, participants were able to employ a functional variability approach for the
265 RJ and SJ, but not the DJ. The rigid technique during DJ may be due to participants not been able to attenuate
266 impact forces upon landing, therefore the drop height may have been too high.

267
268 It may be beneficial for strength and conditioning coaches to expose a range of constrains on vertical jump
269 exercises allowing athletes to gain a wider experience of constraints. This would broaden the athletes experience
270 of constraints allowing a greater functional variability, so jump performance can be better maintained.

271
272 Even though technique variability aids jump performance maintenance it is not known the affect this has on
273 kinetic parameters of the jump. The kinetic parameters are important as they explain the force production that
274 drives movement. Weinhandle et al. investigated the kinetics and kinematics of a DJ under fatigued and none
275 fatigued states (26). Ankle, knee and hip angles at 100 ms after touch down were found to significantly differ
276 between an unfatigued and fatigued state, therefore supporting kinematics to vary between jump repetitions.
277 However, force production during this period did not differ (26), suggesting force production does not change
278 between repetitions of CMJ and therefore kinetic parameters do not vary between repetitions. However, this study
279 only analyses one small period of one type of vertical jump. It is not known if kinematic technique affects kinetic
280 technique during any other period of a DJ, or other types of vertical jumps. Further research is needed to determine
281 this.

282 283 PRACTICAL APPLICATION

284 Variation in vertical jump technique is employed to overcome constraints imposed on the athlete, allowing the
285 athlete to maintain jump performance. Therefore, there is no optimal jump technique for plyometric and ballistic
286 exercises. It may be beneficial for the strength and conditioning coach to train variation during vertical jump

287 exercise. This can be achieved by exposing a range of constraints on vertical jump exercises allowing athletes to
288 gain a wider experience of constraints that may affect them in competition. Incorporation of a range of vertical
289 jump exercises in training would also allow athletes to learn and utilise functional variability, so adaptation to
290 constraints is easier.

291
292 A more rigid vertical jump technique was used for the DJ, as there were fewer differences in kinematic measures.
293 This was due to participants not been able to attenuate impact forces upon landing, suggesting drop height was
294 too high. This highlights to the S&C coach that the athlete is not strong enough, and thus needs to develop strength.
295 Therefore, this is a method an S&C coach can use to identify if their athletes are strong enough to attenuate
296 landing force that may be experience in their sport.

297
298 Vertical jump kinematics differ between plyometric and ballistic exercise, thus there are different jump technique
299 of each exercise. The strength and conditioning coach should be aware of this as it may affect the method of
300 training the technical aspect of a vertical jump.

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387 Table 1: Interclass correlation coefficient results

	Drop Jump	Rebound Jump	Squat Jump
First ground contact	0.975	0.980	0.932
Greatest jump depth	0.962	0.974	0.656
Toe off	0.933	0.963	0.943
Flexion range	0.986	0.927	0.693
Extension range	0.979	0.799	0.961
Flexion time	0.984	0.924	0.974
Extension time	0.972	0.983	0.736
Average angle velocity	0.885	0.923	0.926
Jump height	0.985	0.985	0.998

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Table 2: Exercise set results of the knee joint.

	Drop Jump			Rebound Jump			Squat Jump		
	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3
Jump Height (cm)	42.5 (31.3 - 48.8)	47.6 (36.1 - 54.1)	49.4 (37.4 - 56.3)	53.5 ^c (44.9 - 58.4)	49.3 ^c (40.2 - 54.5)	52.2 ^{a,b,c} (42.6 - 57.6)	62.5 ^{a,b,c} (52.9 - 67.9)	56.3 ^{a,b,c} (46.7 - 62.0)	60.7 ^{a,b,c} (51.2 - 66.3)
First Ground Contact (degrees)	147.0 (142.2 - 151.9)	146.6 (140.7 - 152.6)	146.2 (137.7 - 154.7)	147.1 (142.4 - 151.8)	147.2 (140.2 - 154.3)	147.9 (138.2 - 157.6)	152.1 (147.6 - 156.6)	151.1 (145.7 - 156.5)	151.2 (143.7 - 158.8)
Greatest Jump Depth (degrees)	108.0 (104.5 - 111.5)	107.6 (99.8 - 115.4)	106.8 (96.8 - 116.8)	107.8 (103.9 - 111.6)	107.4 (99.4 - 115.5)	106.5 ^{b,c} (96.2 - 116.7)	95.1 ^{a,b,c,d,e,f} (89.4 - 100.8)	102.7 (81.8 - 123.7)	96.9 ^{a,b,c} (86.4 - 107.3)
Toe Off (degrees)	156.0 (152.1 - 159.9)	155.0 (150.4 - 159.6)	156.1 (149.4 - 162.9)	158.5 (155.5 - 161.5)	157.8 (153.1 - 162.5)	157.1 (149.9 - 164.4)	157.1 (153.1 - 161.1)	156.6 (150.0 - 163.1)	157.5 (149.3 - 165.8)
Flexion Range (degrees)	39.0 (31.5 - 46.6)	40.0 (25.9 - 54.0)	39.3 (21.5 - 57.2)	42.1 (34.0 - 50.3)	39.5 (26.7 - 52.2)	42.2 (25.8 - 58.6)	57.2 ^{a,b,c,d,e,f} (50.6 - 63.8)	49.9 ^{ag} (38.7 - 61.1)	53.0 ^{a,b,d} (42.7 - 63.2)
Extension Range (degrees)	48.0 (42.4 - 53.5)	47.6 (37.3 - 57.9)	49.4 (36.8 - 62.1)	53.5 (47.6 - 59.5)	49.3 (35.2 - 63.4)	52.2 (41.9 - 62.5)	62.5 ^{a,b,c,e,f} (55.6 - 69.4)	56.3 (42.9 - 69.7)	60.7 ^{a,b,c,g} (49.1 - 72.2)
Flexion Time (seconds)	0.13 (0.09 - 0.17)	0.12 (0.07 - 0.17)	0.13 (0.20 - 0.06)	0.19 (0.11 - 0.26)	0.16 (0.09 - 0.23)	0.17 (0.03 - 0.30)	1.42 ^{a,b,c,d,e,f} (1.04 - 1.81)	1.35 ^{a,b,c,d,e,f} (0.84 - 1.85)	1.48 ^{a,b,c,d,e,f} (0.47 - 2.50)
Extension Time (Seconds)	0.14 (0.11 - 0.17)	0.15 (0.10 - 0.21)	0.14 (0.07 - 0.22)	0.40 ^{a,b,c} (0.31 - 0.49)	0.39 ^{a,b,c} (0.26 - 0.52)	0.38 ^{a,b,c} (0.18 - 0.57)	0.51 ^{a,b,c,d,e,f} (0.43 - 0.58)	0.51 ^{a,b,c,d,e,f} (0.44 - 0.57)	0.51 ^{a,b,c,d,e,f} (0.42 - 0.61)
Average Angular Velocity (degrees per second)	81.1 (55.8 - 106.4)	71.3 (32.8 - 109.8)	75.3 (30.6 - 120.0)	69.0 (46.3 - 91.6)	67.3 (34.1 - 100.5)	60.1 (17.4 - 102.9)	22.6 ^{a,b,c,d,e,f} (0.9 - 44.2)	22.9 ^{a,b,c,d,e,f} (-13.8 - 59.6)	34.0 ^{a,b,c,d,e,f} (-24.5 - 92.6)

Data is given as mean (95% confidence intervals).

- a = significantly different ($P < 0.05$) from drop jump set 1
- b = significantly different ($P < 0.05$) from drop jump set 2
- c = significantly different ($P < 0.05$) from drop jump set 3
- d = significantly different ($P < 0.05$) from rebound jump set 1
- e = significantly different ($P < 0.05$) from rebound jump set 2
- f = significantly different ($P < 0.05$) from rebound jump set 3

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	Drop Jump			Rebound Jump			Squat Jump		
	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3
Jump Height (cm)	42.5 (31.3 - 48.8)	47.6 (36.1 - 54.1)	49.4 (37.4 - 56.3)	53.5 ^c (44.9 - 58.4)	49.3 ^c (40.2 - 54.5)	52.2 ^{a,b,c} (42.6 - 57.6)	62.5 ^{a,b,c} (52.9 - 67.9)	56.3 ^{a,b,c} (46.7 - 62.0)	60.7 ^{a,b,c} (51.2 - 66.3)
First Ground Contact(degrees)	149.0 (144.1 - 153.9)	152.2 (146.5 - 157.8)	151.5 (144.2 - 158.9)	157.9 (153.0 - 162.8)	154.5 (147.6 - 161.3)	154.2 (144.0 - 164.3)	153.0 (146.8 - 159.1)	150.1 (140.4 - 159.8)	151.1 (140.6 - 161.7)
Greatest Jump Depth (degrees)	132.5 (124.6 - 140.4)	131.2 (121.2 - 141.2)	131.9 (122.2 - 141.6)	117.0 ^a (101.7 - 132.2)	119.9 ^{a,b,c} (102.4 - 137.4)	118.2 ^{a,b,c} (92.9 - 143.6)	87.0 ^{a,b,c,d,e,f} (77.2 - 96.7)	87.7 ^{a,b,c,d,e,f} (70.4 - 105.1)	87.4 ^{a,b,c,d,e,f} (65.1 - 109.7)
Toe Off (degrees)	168.5 (164.5 - 172.4)	167.0 (163.2 - 170.8)	166.9 (163.5 - 170.3)	162.6 ^{a,b,c} (157.7 - 167.6)	162.6 ^{a,b,c} (155.9 - 169.3)	162.3 ^{a,b,c} (154.2 - 170.5)	156.7 ^{a,b,c,d,e,f} (152.9 - 160.4)	156.8 ^{a,b,c,d,e,f} (151.1 - 162.4)	157.8 ^{a,b,c,d,e,f} (150.8 - 164.8)
Flexion Range (degrees)	18.3 (11.7 - 24.8)	22.8 (9.5 - 36.1)	21.5 (11.1 - 31.8)	39.8 ^{a,c} (26.6 - 53.0)	33.4 ^{a,b,c} (16.7 - 50.1)	37.1 ^{a,c} (10.8 - 63.5)	66.0 ^{a,b,c,d,e,f} (55.2 - 76.9)	60.8 ^{a,b,c,d,e,f} (43.8 - 78.1)	62.5 ^{a,b,c,d,e,f} (37.8 - 87.1)
Extension Range (degrees)	36.2 (29.3 - 43.2)	35.7 (24.5 - 46.8)	36.9 (28.3 - 45.4)	45.7 (34.2 - 57.2)	43.3 ^{b,c} (30.6 - 56.0)	47.5 ^{b,c} (25.9 - 69.1)	70.7 ^{a,b,c,d,e,f} (61.6 - 79.8)	69.0 ^{a,b,c,d,e,f} (54.7 - 83.4)	69.1 ^{a,b,c,d,e,f} (49.0 - 89.2)
Flexion Time (seconds)	0.14 (0.11 - 0.17)	0.13 (0.10 - 0.16)	0.13 (0.10 - 0.16)	0.21 (0.14 - 0.28)	0.19 (0.13 - 0.25)	0.25 (0.13 - 0.37)	1.41 ^{a,b,c,d,e,f} (1.01 - 1.81)	1.31 ^{a,b,c,d,e,f} (0.84 - 1.78)	1.42 ^{a,b,c,d,e,f} (0.46 - 2.38)
Extension Time (Seconds)	0.15 (0.13 - 0.17)	0.35 (-0.06 - 0.77)	0.15 (0.12 - 0.18)	0.38 ^{a,c} (0.28 - 0.49)	0.35 ^{a,c} (0.23 - 0.47)	0.37 ^{a,c} (0.18 - 0.57)	0.56 ^{a,c,d,e,f} (0.46 - 0.65)	0.57 ^{a,c,d,e,f} (0.44 - 0.69)	0.58 ^{a,c,d,e,f} (0.41 - 0.75)
Average Angular Velocity (degrees per second)	77.4 (53.7 - 101.0)	57.4 (32.2 - 82.4)	56.6 (32.6 - 80.6)	22.5 ^{a,b,c} (7.69 - 37.3)	35.2 ^{a,b,c,d} (13.3 - 57.1)	46.6 ^{a,b,c} (-9.7 - 103.0)	3.8 ^{a,b,c,d,e,f} (0.1 - 7.5)	0.7 ^{a,b,c,d,e,f} (-5.1 - 6.4)	9.9 ^{a,b,c,e} (-17.8 - 37.5)

Table 3: Exercise set results of the hip joint.

Data is given as mean (95% confidence intervals).

- a = significantly different ($P < 0.05$) from drop jump set 1
- b = significantly different ($P < 0.05$) from drop jump set 2
- c = significantly different ($P < 0.05$) from drop jump set 3
- d = significantly different ($P < 0.05$) from rebound jump set 1
- e = significantly different ($P < 0.05$) from rebound jump set 2
- f = significantly different ($P < 0.05$) from rebound jump set 3

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	Drop Jump			Rebound Jump			Squat Jump		
	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3
Jump Height (cm)	42.5 (31.3 - 48.8)	47.6 (36.1 - 54.1)	49.4 (37.4 - 56.3)	53.5 ^c (44.9 - 58.4)	49.3 ^c (40.2 - 54.5)	52.2 ^{a,b,c} (42.6 - 57.6)	62.5 ^{a,b,c} (52.9 - 67.9)	56.3 ^{a,b,c} (46.7 - 62.0)	60.7 ^{a,b,c} (51.2 - 66.3)
First Ground Contact(degrees)	113.9 (110.8 - 117.0)	113.4 (109.0 - 117.8)	113.4 (106.2 - 120.6)	109.4 (105.0 - 113.8)	110.2 (104.4 - 116.0)	109.4 (118.2 - 100.6)	89.1 (87.4 - 90.7)	88.0 (80.9 - 95.1)	88.9 (85.8 - 92.1)
Greatest Jump Depth (degrees)	72.6 (70.7 - 74.4)	72.5 (69.3 - 75.8)	72.1 (67.2 - 77.0)	69.6 (66.6 - 72.7)	69.5 ^{a,b,c} (64.8 - 74.3)	69.1 (64.0 - 74.1)	69.5 ^{a,b,c,d,e,f} (67.0 - 72.1)	72.9 ^{a,b,c,d,e,f} (61.6 - 84.2)	70.1 ^{a,b,c,d,e,f} (64.3 - 75.8)
Toe Off (degrees)	112.0 (109.7 - 114.3)	111.2 (197.8 - 114.6)	111.1 (107.2 - 114.9)	110.8 (108.9 - 112.7)	111.2 (108.5 - 113.9)	112.3 (107.1 - 117.5)	112.8 ^d (110.3 - 115.2)	111.0 (101.2 - 120.8)	114.4 ^{c,d,e,f} (108.8 - 120.0)
Flexion Range (degrees)	41.4 (38.4 - 44.3)	40.9 (36.4 - 45.3)	41.6 (35.2 - 47.9)	39.8 (35.9 - 43.6)	41.9 (35.9 - 43.6)	40.2 (31.9 - 48.5)	57.2 ^{a,b,c,d,e,f} (50.6 - 63.8)	49.9 ^{b,d,e,f} (38.7 - 61.1)	53.0 ^{a,b,c,d,e,f} (42.7 - 63.2)
Extension Range (degrees)	39.4 (37.3 - 41.4)	39.5 (34.7 - 44.3)	39.0 (34.4 - 43.5)	41.4 ^c (38.7 - 44.0)	40.0 (35.1 - 44.9)	41.7 ^c (38.6 - 44.8)	41.7 ^{a,c} (39.1 - 44.3)	42.6 ^{a,c} (39.2 - 46.0)	43.0 ^{a,c} (38.6 - 47.3)
Flexion Time (seconds)	0.14 (0.11 - 0.17)	0.12 (-0.61 - 0.48)	0.13 (0.08 - 0.19)	0.20 (0.13 - 0.27)	0.17 (0.11 - 0.24)	0.20 (0.06 - 0.33)	1.11 ^{a,b,c,d,e,f} (0.68 - 1.53)	1.03 ^{a,b,c,d,e,f} (0.44 - 1.61)	0.76 ^{a,b,c,d,e,f} (0.10 - 1.42)
Extension Time (Seconds)	0.15 (-0.75 - 0.45)	0.35 (-0.26 - 0.96)	0.15 (0.10 - 0.21)	0.33 ^c (0.29 - 0.37)	0.34 ^c (0.27 - 0.37)	0.32 ^c (0.21 - 0.43)	0.32 ^{b,c} (0.25 - 0.38)	0.29 ^{b,c} (0.12 - 0.47)	0.31 ^{b,c} (0.11 - 0.52)
Average Angular Velocity (degrees per second)	21.0 (10.2 - 31.7)	24.4 (9.1 - 39.7)	33.3 (-3.6 - 70.1)	26.6 (16.2 - 37.1)	25.6 (10.6 - 40.6)	26.0 (4.1 - 47.6)	22.3 (14.5 - 30.1)	19.6 (31.4 - 7.8)	23.9 (6.4 - 41.5)

Table 4: Exercise set results of the ankle joint.

Data is given as mean (95% confidence intervals).

- a = significantly different ($P < 0.05$) from drop jump set 1
- b = significantly different ($P < 0.05$) from drop jump set 2
- c = significantly different ($P < 0.05$) from drop jump set 3
- d = significantly different ($P < 0.05$) from rebound jump set 1
- e = significantly different ($P < 0.05$) from rebound jump set 2
- f = significantly different ($P < 0.05$) from rebound jump set 3

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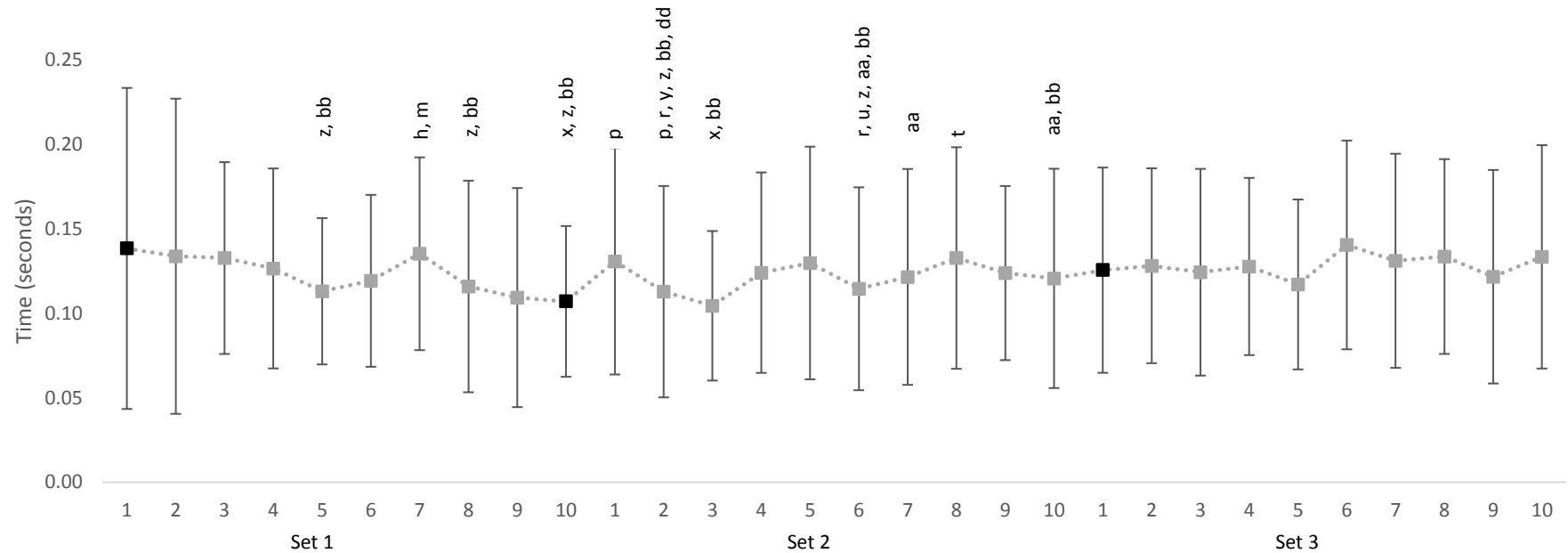
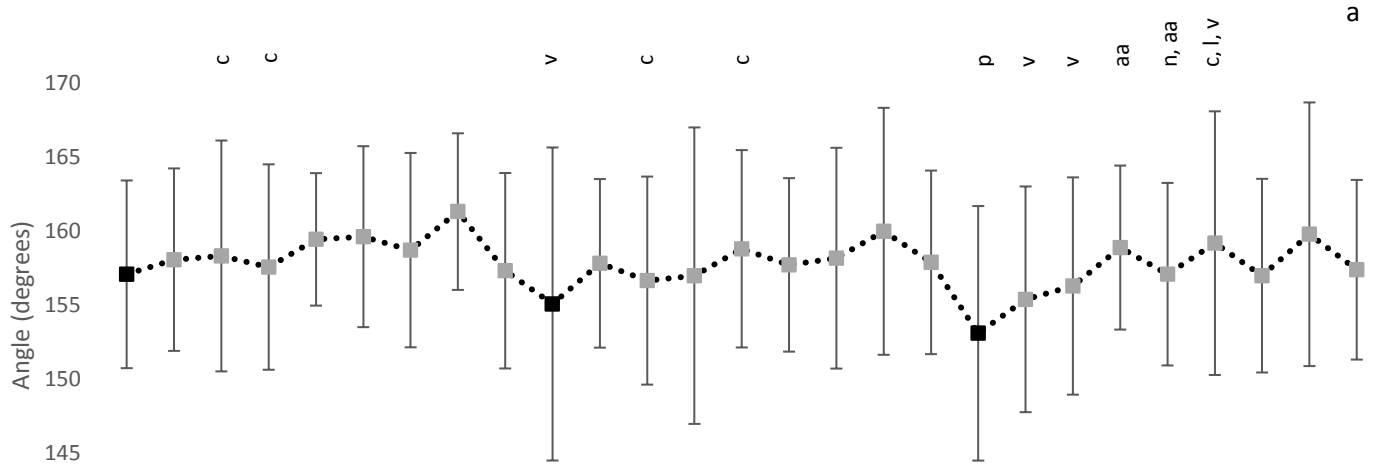


Figure 1: Drop jump exercise repetition knee flexion time result. Black marker denotes first repetition of each set. Error bars represent SD. Significance set at $P < 0.05$.

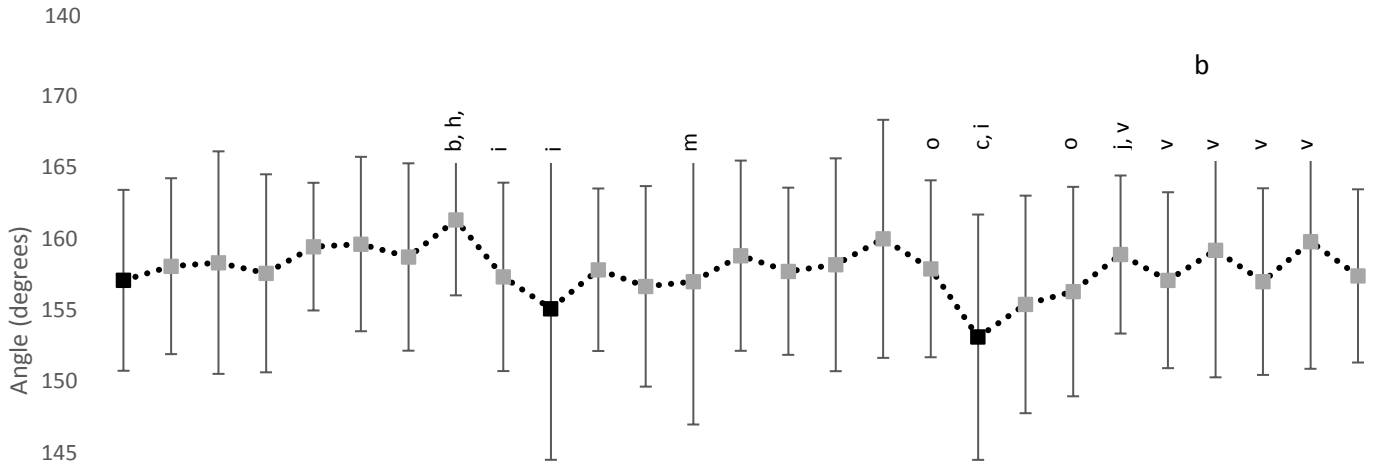
h = significant different to set 1 repetition 8, m = significant different to set 2 repetition 3, p = significant different to set 2 repetition 6, r = significant different to set 2 repetition 8, t = significant different to set 2 repetition 10, u = significant different to set 3 repetition 1, x = significant different to set 3 repetition 4, y = significant different to set 3 repetition 5, z = significant different to set 3 repetition 6, bb = significant different to set 3 repetition 8, dd = significant different to set 3 repetition 10

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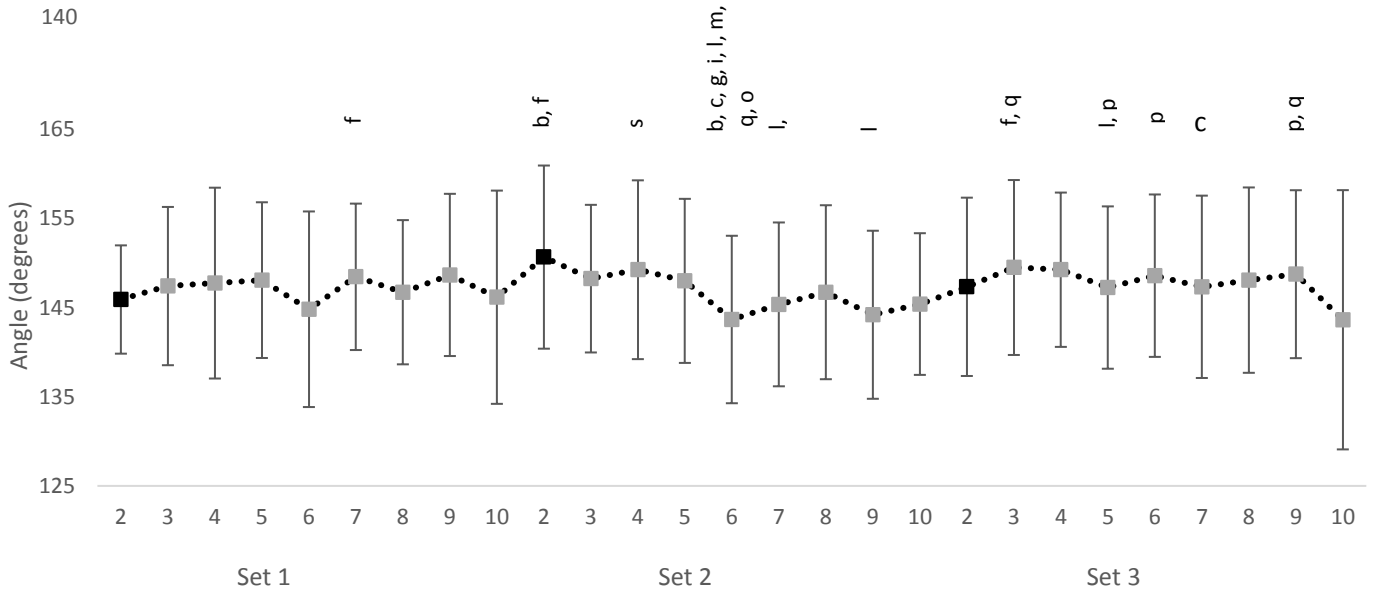
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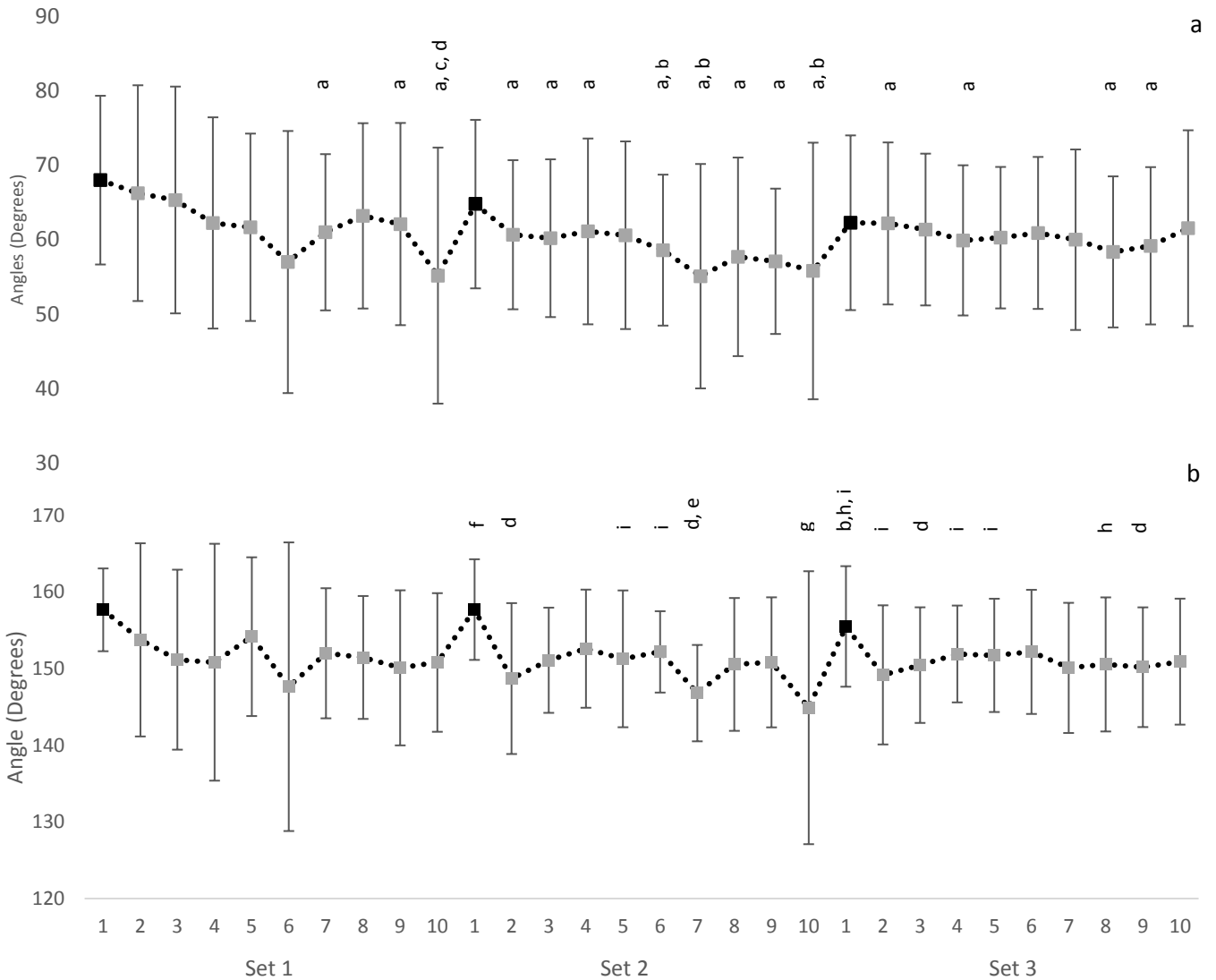


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7 **Figure 2a. Rebound jump exercise repetition knee joint flexion time result. 2b. Rebound**
8 **jump exercise repetition knee joint angle at take-off result. 2c. Rebound jump exercise**
9 **repetition knee joint angle at touch down result. Black marker denotes first repetition of**
10 **each set. Error bars represent SD. Significance set at $P < 0.05$.**

11 **a = significant different to set 1 repetition 2, b = significant different to set 1 repetition 3, c =**
12 **significant different to set 1 repetition 6, d = significant different to set 1 repetition 7, e =**
13 **significant different to set 1 repetition 8, f = significant different to set 1 repetition 9, g =**
14 **significant different to set 1 repetition 10, h = significant different to set 2 repetition 2, i =**
15 **significant different to set 2 repetition 3, j = significant different to set 2 repetition 4, k =**
16 **significant different to set 2 repetition 5, l = significant different to set 2 repetition 6, m =**
17 **significant different to set 2 repetition 7, n = significant different to set 2 repetition 9, o =**
18 **significant different to set 3 repetition 2, p = significant different to set 3 repetition 7.**

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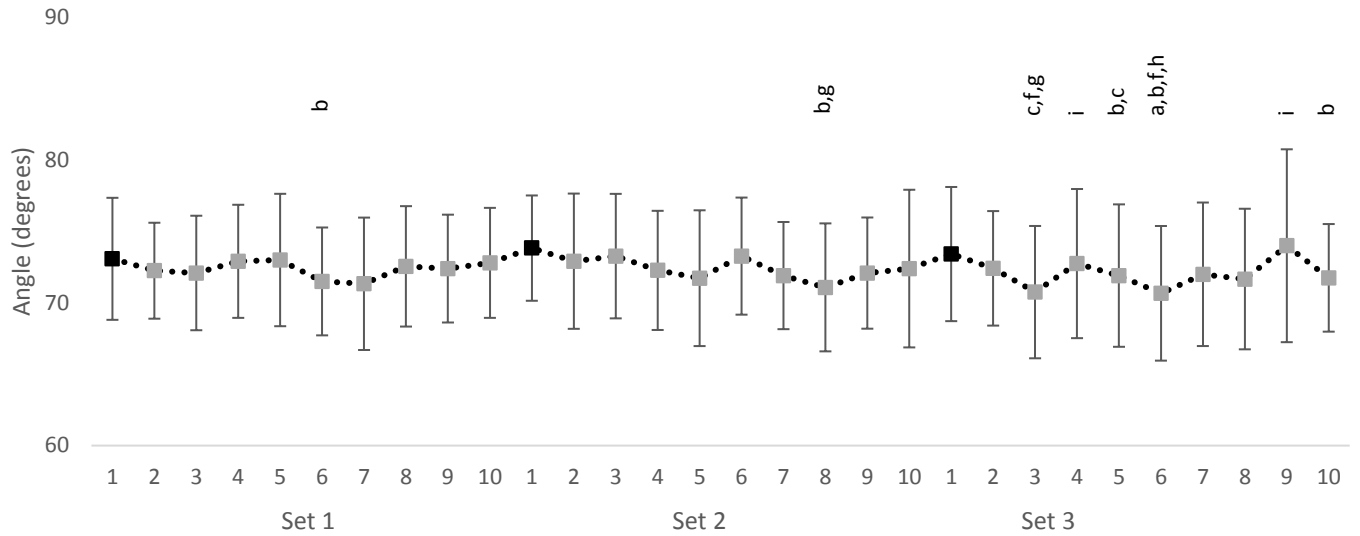
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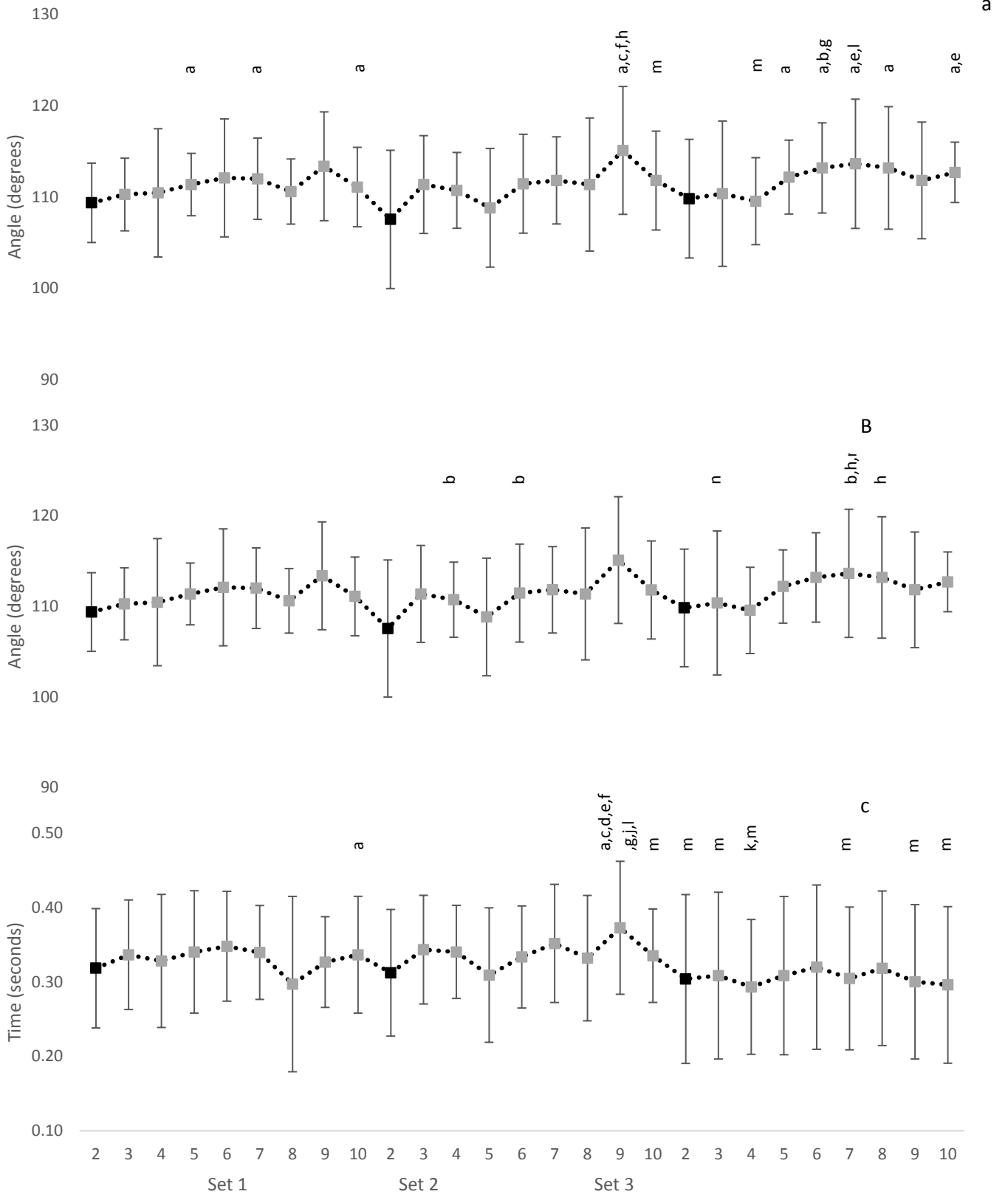
Figure 3a. Squat jump exercise repetition knee joint extension range result. 3b. squat jump exercise repetition knee joint angle at touch down result. Error bars represent SD. Black marker denotes first repetition of each set. Significance set at $P < 0.05$. a = significant different to set 1 repetition 2, b = significant different to set 1 repetition 3, c = significant different to set 1 repetition 4, d = significant different to set 1 repetition 5, e = significant different to set 1 repetition 8, f = significant different to set 1 repetition 9, g = significant different to set 1 repetition 10, h = significant different to set 2 repetition 4, i = significant different to set 2 repetition 7.



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Figure 4: Drop jump exercise repetition ankle joint angle at peak joint flexion result. Black marker denotes first repetition of each set. Error bars represent SD. Significance set at $P < 0.05$. a = significant different to set 1 repetition 3, b = significant different to set 1 repetition 4, c = significant different to set 1 repetition 5, d = significant different to set 1 repetition 8, e = significant different to set 2 repetition 2, f = significant different to set 2 repetition 3, g = significant different to set 2 repetition 4, h = significant different to set 2 repetition 6, i = significant different to set 2 repetition 8.

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102 **Figure 5a. Rebound jump exercise repetition ankle joint angle at take-off result. 5b. Rebound**
103 **jump exercise repetition ankle joint flexion time result. 5c. Rebound jump exercise repetition**
104 **ankle joint extension time result. Black marker denotes first repetition of each set. Error**
105 **bars represent SD. Significance set at $P < 0.05$.**

106 **a = significant different to set 1 repetition 2, b = significant different to set 1 repetition 3, c =**
107 **significant different to set 1 repetition 4, d = significant different to set 1 repetition 5, e =**
108 **significant different to set 1 repetition 8, f = significant different to set 2 repetition 2, g =**
109 **significant different to set 2 repetition 3, h = significant different to set 2 repetition 4, i =**
110 **significant different to set 2 repetition 5, k = significant different to set 2 repetition 7, l =**
111 **significant different to set 2 repetition 8, m = significant different to set 2 repetition 9, n =**
112 **significant different to set 3 repetition 2, o = significant different to set 3 repetition 5, p =**
113 **significant different to set 2 repetition 6.**

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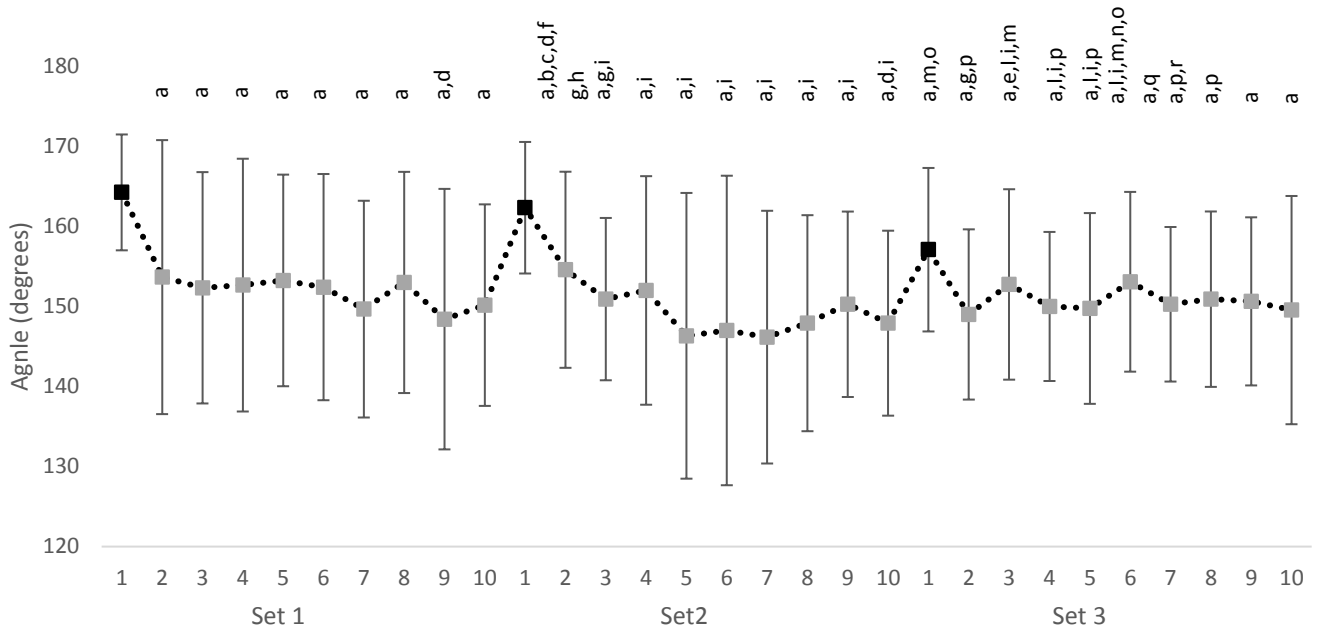
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149 **Figure 6: Squat jump exercise repetition hip joint angle at toe land result. Black marker**
 150 **denotes first repetition of each set. Error bars represent SD. Significance set at $P < 0.05$.**

151 **a = significant different to set 1 repetition 1, b = significant different to set 1 repetition 3, c =**
 152 **significant different to set 1 repetition 4, d = significant different to set 1 repetition 5, e =**
 153 **significant different to set 1 repetition 7, f = significant different to set 1 repetition 8, g =**
 154 **significant different to set 1 repetition 9, h = significant different to set 1 repetition 10, i =**
 155 **significant different to set 2 repetition 1, k = significant different to set 2 repetition 4, l =**
 156 **significant different to set 2 repetition 5, m = significant different to set 2 repetition 7, n =**
 157 **significant different to set 2 repetition 8, o = significant different to set 2 repetition 10, p =**
 158 **significant different to set 3 repetition 1, q = significant different to set 3 repetition 4, r =**
 159 **significant different to set 3 repetition 6**
 160