

Specific adaptations in performance and muscle architecture after weighted jump-squat vs body mass squat jump training in recreational soccer players.

Running head: Weighted vs body mass jump-squat training

The study was conducted at the Department of Neurological, Biomedical and Movement Sciences, University of Verona, Italy.

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1 **ABSTRACT**

2 The aim of the present study was to compare the effects of weighted **jump squat** (WJST) vs **body**
3 **mass squat jump training** (**BMSJT**) on quadriceps muscle architecture, **lower-limb** lean-mass
4 (LM) and muscle strength, performance in change of direction (COD), sprint and jump in
5 recreational soccer-players. Forty-eight healthy soccer-players participated in an off-season
6 randomized controlled-trial. Before and after an eight-week training intervention, *vastus lateralis*
7 pennation angle, fascicle length, muscle thickness, LM, squat 1-RM, quadriceps and hamstrings
8 isokinetic peak-torque, agility T-test, 10 and 30m sprint and squat-jump (SJ) were measured.
9 Although similar increases in muscle thickness, fascicle length increased more in WJST (ES=1.18,
10 0.82-1.54) than in **BMSJT** (ES=0.54, 0.40-0.68) and pennation angle only increased in **BMSJT**
11 (ES=1.03, 0.78-1.29). Greater increases in LM were observed in WJST (ES=0.44, 0.29-0.59) than
12 in **BMSJT** (ES=0.21, 0.07-0.37). Agility T-test (ES=2.95, 2.72-3.18), 10m (ES=0.52, 0.22-0.82)
13 and 30m-sprint (ES=0.52, 0.23-0.81) improved only in WJST, while SJ improved in **BMSJT**
14 (ES=0.89, 0.43-1.35) more than in WJST (ES=0.30, 0.03-0.58). Similar increases in **squat 1-RM**
15 and peak-torque occurred in both groups. The greater inertia accumulated within the landing-phase
16 in WJST vs **BMSJT** has increased the eccentric workload, leading to specific eccentric-like
17 adaptations in muscle architecture. The selective improvements in COD in WJST may be related to
18 the increased braking ability generated by the enhanced eccentric workload.

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20

21 **Key-words:** Change of direction; sprint; fascicle length; isokinetic; ballistic training; pennation
22 angle

23

24

25 **INTRODUCTION**

26 Ballistic training is often used to improve skeletal muscle function and athletic performance (15). In
27 ballistic exercise, the athletes has to exert the highest strength in the shortest time to maximally
28 accelerate **their** body mass (e.g., jumping) or an object (e.g., kicking or throwing a ball). Jump-
29 squat **is** among the most used ballistic exercise to enhance mechanical power in lower-limb muscles
30 (15,25,30). **Jump-squat has been shown to improve jump height** (17,25,38), as well as sprint
31 performance (15,16,38). However, since the increased role of change of direction (COD) in soccer
32 (8), the effects of jump-squat training on COD were only recently investigated, reporting
33 improvements in COD after **jump-squat training only (26,27), or jump-squat added to a**
34 **traditional strength training program (23). Importantly, jump-squat training was shown to**
35 **improve physical ability in soccer players in pre-season (27) and to counteract the decrease in**
36 **speed and power performance due to the high endurance training load the players undergo**
37 **before the season begins (28). Additionally, jump-squat training was effectively added to**
38 **traditional soccer training to elicit power in-season (35). Finally, in order to get meaningful**
39 **adaptations, jump-squat training was carried out for six weeks or more (15,16,23,26,27,35).**

40
41 Muscle architecture, encompassing muscle thickness, pennation angle and fascicle length, is a
42 strong determinant of muscle force generating capacity (5). Muscles with longer fascicles **can**
43 develop force at a higher rate, while muscles with wider thickness and pennation angle have a larger
44 physiological cross-sectional area, thus enhancing the maximal force **produced** (5). Muscle
45 thickness, pennation angle and fascicle length are known to increase after traditional resistance
46 training (3,11,20,32). However, little is known about the effects of jump-squat training on muscle
47 architecture. Previous studies have examined the effects of jump-squat training using quadriceps
48 muscle as the target muscle because of its **influential** role in jumping tasks (19).

49

50 However, inconsistent results, such as increases in pennation angle but not in muscle thickness **in**
51 *vastus lateralis* (15) or increases in muscle thickness after a combined strength and jump-squat
52 training in *rectus femoris* (35), have been recently reported. **Such a discrepancy could have**
53 **derived from the different targeted muscles, and from the different protocols used. Indeed,**
54 **given that some Olympic-lift exercises were included in the latter (35), the larger knee-range**
55 **of movement compared to the self-selected depth used in jump-squat training may have**
56 **resulted in a greater work completed.** Moreover, no change in fascicle length after combined
57 strength/jump training (36) nor after combined jump/sprint training was observed (4).

58
59 Jump-squat training has been shown to improve **lower-limb** isometric muscle strength (15), **as well**
60 **as to** increase squat 1-RM (16,25,30). Given the important contribution of the quadriceps and
61 hamstrings during both take-off and landing in jump-squat (19), **training using jump-squat** may
62 have specific effects on the maximal strength of these muscle groups. A previous surface
63 electromyographic study highlighted **that a higher hamstrings activity in both concentric and**
64 **eccentric phase occurred when jumps are performed without a stretch-shortening cycle (31).**
65 **Since jump-squat does not include a fast countermovement or a plyometric action, the**
66 **repetitive jumps may result in a noteworthy specific strength adaptation in the hamstrings.**
67 **Interestingly, it was shown that quadriceps muscle activation was not affected by the load (21)**
68 **leading to hypothesize that** specific adaptations in the hamstrings-to-quadriceps strength ratio, an
69 index to estimate hamstring injury risk (9), **may be derived from jump-squat training.**
70 **Interestingly, greater fatigue was shown in the hamstrings compared with the quadriceps**
71 **after a standardized task (10) or after a soccer match simulation (9). Therefore, jump-squat**
72 **training may be used to increase hamstrings strength, consequently increasing the**
73 **hamstrings-to-quadriceps strength ratio (9,10), therefore decreasing the hamstrings strain**
74 **injury risk.**

75

76 Several previous studies have investigated the effect of jump-squat training using the external load
77 that maximized the power output (15–17,38). However, measuring such a load appropriately
78 requires devices (i.e. force plates and linear transducers) that are often unavailable in the field
79 **setting**. Notwithstanding, it was reported that the maximal power output usually ranges from 0% to
80 30% of the squat 1-RM (14,18,30), **and also shown in a direct optimum load vs body mass**
81 **comparison** (29). Jump-squat training is characterized by repetitive explosive concentric take-offs
82 followed by repetitive eccentric landings. Both work and force developed during these phases are
83 accounted for the external load used during the jump-squat. Particularly, **compared to body mass**
84 **squat jump, a greater inertia accumulated during a weighted jump** results in a greater eccentric
85 work completed, which was shown to be a key-factor for inducing improvements in muscle
86 performance (17). **Previous studies have shown that irrespective of the exercise**, an accentuated
87 eccentric phase induced specific adaptations in muscle architecture **after isokinetic or isoload**
88 **knee-extension training** (11) or greater hypertrophic stimuli **after a six-week bench press**
89 **training**. (13). Finally, the repeated excessive braking-load during landing could result in greater
90 improvements in COD, which similarly requires the athletes to repetitively brake the inertia of their
91 body mass and subsequently accelerate.

92 Therefore, the aim of the present study was to evaluate the effects of weighted (with 30% of squat
93 1-RM) jump-squat training (WJST) or **body mass squat-jump training (BMSJT)** on quadriceps
94 muscle architecture and **lower-limb** lean mass (LM) in recreational soccer players. COD, sprint and
95 jump performance were also evaluated. Lastly, both **changes in** hamstrings and quadriceps peak
96 torque were measured **as well as the** changes in functional $H_{ecc}:Q_{conc}$ ratio was **calculated**.

97

98

99 **METHODS**100 **Experimental approach to the problem**

101 The present investigation was designed as a pre-post, parallel three-groups, randomized-controlled
102 trial. Using a restricted-blocks randomization (computer-generated sequence), the participants were
103 randomly allocated into **BMSJT** or **WJST** or control group (CON). The allocation and the
104 randomization were completed by one of the researchers without any contact or knowledge of the
105 participants. Therefore, no allocation concealment-mechanisms were necessary. To calculate the
106 sample size, a statistical software (GPower, Dusseldorf, Germany) was used. Given the study
107 design (3 groups, 2 repeated measures), the effect size = 0.25 (medium), α -error < 0.05, the non-
108 sphericity correction $\epsilon = 1$, the correlation between the repeated measures = 0.5 and a desired power
109 (1- β error) = 0.8, the total sample size resulted in 42 participants. To prevent **the effect of any**
110 **possible drop-out on the statistical power**, 48 participants were included.

111

112 **Participants**

113 Forty-eight male recreational soccer players (age: 21 ± 3 years, **age ranged from 18 to 25 years;**
114 **body-mass: 73 ± 4 Kg; height: 1.78 ± 0.10 m)** volunteered to participate in the present investigation.
115 The participants joined two Italian recreational soccer teams, which competed in a recreational
116 soccer championship. **The participants had a soccer history of at least five consecutive years in**
117 **young or recreational soccer teams. Within the previous season, their typical training volume**
118 **consisted of three training sessions (about 2 hours per session) plus one match per week, from**
119 **September to May. Lower-limb** muscular or joint injuries in the previous 12 months, as well as
120 cardio-pulmonary diseases, smoking or drugs use, were listed as exclusion criteria. The present
121 investigation was approved by the local Ethical Committee and was in line with the Declaration of
122 Helsinki (1975 and further updates) concerning the ethical standards in studies involving human
123 subjects. Finally, the participants were carefully informed about any possible risks due to the
124 investigation's procedures, and they signed a written informed consent.

125 **Procedures**

126 To evaluate the **lower-limb** muscle strength, squat 1-RM, isokinetic concentric, eccentric and
127 isometric quadriceps peak-torque and eccentric hamstrings peak-torque were measured. To evaluate
128 the quadriceps muscle architecture, muscle thickness, fascicle length and pennation angle were
129 measured on *vastus lateralis* muscle. To evaluate the **lower-limb** (LM), dual-energy X-ray
130 absorptiometry (DXA) scans were used. Finally, to evaluate their soccer abilities, change of
131 direction (COD), sprinting- and jumping-ability were measured.

132

133 The present investigation lasted 10 weeks and was carried out in the off-season (from May to July).
134 The participants were instructed to avoid any other form of resistance training for the entire
135 duration of the present investigation. In the first week, the participants were involved in three
136 testing-sessions. In the first session, the participants were familiarized with the squat technique,
137 isokinetic strength testing procedures, COD, sprinting- and jumping-ability testing-procedures.
138 Within the second session, muscle architecture, LM and squat 1-RM were measured, and the
139 participants familiarized with the training protocols. Within the third session, isokinetic strength,
140 COD, sprinting- and jumping-ability was measured. The intervention lasted eight weeks. Finally,
141 the post-training testing measurements were assessed the week after the end of the intervention and
142 **they were** conducted over two sessions. In the first one, muscle architecture, LM, squat 1-RM and
143 isokinetic strength were measured. In the second session, COD, sprinting and jumping abilities
144 were measured. **Each assessment was performed by the same experienced operators and**
145 **interspersed by 30 min of passive recovery. COD, sprints and jumps were measured indoor,**
146 **on a concrete surface.**

147

148

Squat 1-RM

149 **Squat 1-RM**
150 The back squat 1-RM was measured using an Olympic bar. After a standardized warm-up,
151 consisting of 30 weight-free squats, the 1-RM attempts started from 80% of the body mass.
152 Thereafter, additional 5% was added until failure. Each set was separated by 3 min of passive
153 recovery. A standard time under tension (2 s for the concentric and eccentric phase, 1s for the
154 isometric phase) was used and the participants had to lower the bar until the thighs were parallel to
155 the ground. Strong standardized encouragements were provided to the participants to maximally
156 perform each trial. Squat 1-RM / body mass was calculated and inserted into the data analysis.
157 Lastly, the 30% of squat 1-RM was used as overload for WJST.

158

Isokinetic measurements

160 An isokinetic dynamometer (Cybex Norm, Lumex, Ronkonkoma, USA) was used to measure
161 quadriceps' and hamstrings' strength. The procedures followed previous recommendations (11).
162 Briefly, the device was calibrated according to the manufacturer's procedures and the centre of
163 rotation was aligned with the tested knee. The participants were seated on the dynamometer's chair,
164 with their trunks slightly reclined backwards and a hip angle of 95°. Two seatbelts secured the trunk
165 and one strap secured the tested limb, while the untested limb was secured by an additional lever.
166 The strength measurements were preceded by a standardized warm-up, consisting of three sets x 10
167 repetitions of weight-free squats. Quadriceps peak-torque was measured in concentric ($1.05 \text{ rad} \cdot \text{s}^{-1}$)
168 and eccentric ($-1.05 \text{ rad} \cdot \text{s}^{-1}$) modalities (12). Hamstrings peak-torque was measured in eccentric
169 ($-1.05 \text{ rad} \cdot \text{s}^{-1}$) modality. Each testing-modality consisted of three maximal trials and was separated
170 by 2 min of passive recovery. Strong standardized encouragements were provided to the
171 participants to maximally perform each trial.

172

173 The peak-torque was then calculated and inserted into the data analysis. Finally, the hamstrings-to-
174 quadriceps strength ratio, defined as the ratio between eccentric hamstrings-to-concentric
175 quadriceps peak torque (i.e., functional $H_{ecc}-Q_{conc}$ ratio) (9) was also calculated. **Excellent test-**
176 **retest reliability was found for all the isokinetic measurements (from $\alpha = 0.915$ to $\alpha = 0.963$).**

177

178 **Muscle architecture**

179 *Vastus lateralis* muscle architecture was measured using an ultrasound device (Acuson P50,
180 Siemens, Germany) at the 39% of the distal length of the thigh (12). The participants laid supine
181 and the 4 cm ultrasound transducer was oriented perpendicularly to the skin surface of the *vastus*
182 *lateralis* and longitudinally to the muscle's fascicles. Two images were scanned and then analysed
183 using a free imaging analysis software (ImageJ, NIH, Maryland, USA). Images were obtained at
184 50% of the muscle width defined as the midpoint between the fascia separating the *vastus lateralis*
185 and *rectus femoris*, and fascia separating the *vastus lateralis* and *biceps femoris* muscles. Muscle
186 thickness was defined as the distance between the superficial and deep aponeurosis. Pennation
187 angle was defined as the angle between the fascicles and the aponeurosis. Finally, fascicle length
188 was calculated according to the formula (5):

$$189 \text{ FL} = \frac{\sin(y+90^\circ) * \text{MT}}{\sin[180^\circ-(y+180^\circ-\text{PA})]}$$

190 where y is the angle between the superficial and the deeper aponeurosis, PA is the pennation angle,
191 and MT is the muscle thickness. The same experienced operator performed the data collection, and
192 data analysis and the operator was blinded to the participants' allocation. **Excellent reliability was**
193 **found for muscle thickness ($\alpha = 0.917$) and pennation angle ($\alpha = 0.902$) and good reliability for**
194 **fascicle length ($\alpha = 0.876$).**

195

196

197 **Lower-limb lean-mass**

198 Total body and regional composition were evaluated using DXA, a total body scanner (QDR
199 Explorer W, Hologic, MA, USA; fan-beam technology, software for Windows XP version 12.6.1),
200 according to the manufacturer's procedures. The DXA body composition approach assumes that the
201 body consists of three components that are distinguishable by their X-ray attenuation properties: fat
202 mass, LM and bone mineral (34). The scanner was calibrated daily against the standard supplied by
203 the manufacturer to avoid possible baseline drift. Whole-body scanning time was about seven min.
204 Data were analysed using standard body region markers: upper and lower extremities, head, and
205 trunk (pelvic triangle plus chest or abdomen). All scanning and analyses were performed by the
206 same operator to ensure consistency. The whole **lower-limb** LM amount was reported in data
207 analysis.

208

209 **Squat jump and counter-movement jump**

210 The peak heights of squat jump (SJ) and counter-movement jump (CMJ) were investigated using an
211 infrared device (OptoJump, Microgate, Italy). In the SJ, the participants were instructed to stand,
212 flex the knees to approximately 90° and jump. The participants had to avoid as much as possible
213 any countermovement, and they were instructed to stop for 2 s at each phase. In the CMJ, the
214 participants were instructed to stand, lower themselves to a self-selected knee flexion and
215 immediately jump. Arms were placed on the hips in both SJ and CMJ tests. The participants were
216 instructed to avoid any knee-flexion before the landing in both SJ and CMJ, and the operator
217 visually checked for it. Three attempts were performed for each jump, and the peak-height was
218 inserted into the data analysis. Two min of passive rest separated each jump. **A good reliability was**
219 **found for SJ ($\alpha = 0.876$), CMJ ($\alpha = 0.861$)**

220

221

Sprint and COD

The time-trials of 10 m and 30 m dash and agility T-test (7) were separately investigated using an infrared device (Polifemo, Microgate, Italy). The participants were placed 30 cm behind the starting line, with the preferred foot in forward position and autonomously started each trial. **An excellent reliability was found for 10 m and 30m sprint ($\alpha = 0.945$ and $\alpha = 0.921$, respectively).**

Agility T-test was performed turning right or left as first, and the sum of the two trials was inserted in the data analysis. Four cones were arranged in a T-shape, with a cone placed 9.14 m from the starting cone (photocell gates 2 m apart) and two further cones placed 4.57 m on either side of the second cone. The participants had to sprint forward 9.14 m from the start line to the first cone and touch the cone with their right hand, shuffle 4.57 m left to the second cone and touch it with their left hand, then shuffle 9.14 m right to the third cone and touch it with their right hand, and shuffle 4.57 m back left to the middle cone and touch it with their left hand before finally back pedalling to the start line. The trials were not considered if participants failed to touch a designated cone or failed to face forward at all times. Only one timing gate placed on the start-finish line was used for timing the T-test. Each test was repeated three times, and the best performance was calculated and inserted into the data analysis. Two min of passive rest separated each trial. **Agility t-test showed a good reliability ($\alpha = 0.818$).**

Intervention

Both **BMSJT** and **WJST** sessions involved a warm-up consisting of 5 min of cycling followed by 20 weight-free squats. **Training volume load was calculated as a number of repetitions * load, assuming a similar time under tension and distance covered (13). Particularly, load referred to body mass, resulting in 1 A.U. (= body mass only) in BMSJT and 1.2 A.U. in WJST (as shown in table 3). To equalize the training volume over the whole intervention, BMSJT performed five sets * 10 repetitions (n = 50), and WJST initially performed four sets * 10 repetitions (n = 40).**

248 **After four weeks, in WJST only, the load was increased to 1.25 A.U. and WJST performed**
249 **two sets * 10 and two sets * 11 repetitions (n = 42). The sets were separated by three min of**
250 **passive recovery.** Both groups were instructed to maximally jump and finish the landing phase of
251 each jump at a knee-angle corresponding approximately to 90°. **BMSJT** were instructed to keep
252 their hands on their hips for the full duration of each jump. In WJST, the overload consisted of a bar
253 grasped on the shoulder in a back-squat position for the whole duration of each jump. The weight
254 used as the external load in WJST was tailored according to the individual squat 1-RM results. The
255 participants received strong standardized encouragements to maximally perform each jump. The
256 intervention lasted eight weeks, two sessions per week, separated by at least two days, during which
257 CON did not perform any training.

258

259 **Statistical analysis**

260 Statistical analysis was performed using statistical software (SPSS 22, IBM, USA). The normality
261 of the distribution was checked using Shapiro–Wilk’s test. The sphericity assumption was
262 calculated using the Mauchly’s test. The test–retest reliability was measured using an intraclass
263 correlation coefficient (ICC, Cronbach- α) and interpreted as follows: $\alpha \geq 0.9 = excellent$; $0.9 > \alpha \geq$
264 $0.8 = good$; $0.8 > \alpha \geq 0.7 = acceptable$; $0.7 > \alpha \geq 0.6 = questionable$; $0.6 > \alpha \geq 0.5 = poor$ (37). The
265 variations of the dependent parameters were analysed by separate mixed-factors ANOVA (time \times
266 group) for repeated measurements. Additionally, data were log-transformed and analysed using an
267 ANCOVA, considering baseline values as covariate. Post-hoc analysis using Bonferroni’s
268 correction was then performed to calculate the main effect for group (three levels: **BMSJT**, WJST,
269 and CON) and time (two levels: pre- and post-training). Significance was set at $\alpha < 0.05$. Data are
270 reported as mean with standard deviation (SD). Changes are reported as %change with 95% of
271 confidence intervals (CI95%) and effect-size (ES) with CI95%. ES was interpreted following the
272 Hopkins’s recommendations (24): 0.0 to 0.2 = *trivial*; 0.2 to 0.6 = *small*; 0.6 to 1.2 = *moderate*; 1.2
273 to 2.0 = *large*; >2.0 *very large*.

274 **RESULTS**

275 **The compliance rate for BMSJT and WJST was 94% and 96%, for a total of 16 and 11**
276 **missed training sessions, respectively. No injury occurred during the intervention period.**

277 Time x group interactions were found for muscle thickness ($p = 0.013$), pennation angle ($p =$
278 0.023) and fascicle length ($p = 0.003$). However, despite the similar increases in muscle thickness
279 (**BMSJT** = *moderate* and **WJST** = *small*), pennation angle *moderately* increased only in **BMSJT**,
280 while greater increases in fascicle length were found in **WJST** compared to **BMSJT** (+8%, CI95%
281 2 to 15). Finally time x group interaction was found for **lower-limb** LM ($p < 0.001$) and greater
282 increases in LM were found in **WJST** compared to **BMSJT** (+7%, CI95% 5 to 10). **CON** did not
283 show any change. (Table 1)

284 Please insert table 1 here

285
286 Significant time x group interaction was found for agility T-test ($p < 0.001$). *Very large* decreases in
287 agility T-test time were observed in **WJST**, while no change occurred in **BMSJT**. Significant time x
288 group interactions were found for 10 m ($p = 0.001$) and 30 m ($p = 0.012$) performance. *Moderate*
289 decreases in 10 m and 30 m sprint time occurred in **WJST** and not in **BMSJT**. Significant time x
290 group interactions were found for SJ ($p = 0.003$) and CMJ ($p = 0.001$). Although both **BMSJT** and
291 **WJST** increased SJ and CMJ height, greater increases occurred in **BMSJT** than **WJST** in SJ (+5%,
292 CI95% 2 to 8) and in CMJ (+6%, CI95% 1 to 11). **CON** did not show any change. (Table 2)

293 Please insert table 2 here

294
295 Time x group interactions were found for squat 1-RM ($p = 0.021$), concentric ($p < 0.001$), eccentric
296 ($p < 0.001$) peak-torque and hamstrings' eccentric peak-torque ($p < 0.001$). Both **BMSJT** and
297 **WJST** similarly increased quadriceps' and hamstrings' muscle strength over time. Similarly, time x
298 group interaction was found for functional H_{ecc} to Q_{conc} ratio ($p < 0.001$). Only **BMSJT** *moderately*
299 increased it. **CON** did not show any change (Table 3).

300 Please insert table 3 here

301

302 **DISCUSSION**

303 The present investigation highlighted that: i) despite the similar increments in *vastus lateralis*
304 muscle thickness, pennation angle widened only after **BMSJT**, while fascicle length increased more
305 after WJST than in **BMSJT**; this was accompanied by greater increases in **lower-limb** LM in WJST
306 compared to **BMSJT**; ii) only WJST improved COD and sprint performance, while **BMSJT**
307 improved jumping ability more than WJST; and iii) similar increases in hamstrings and quadriceps
308 muscle strength occurred in both **BMSJT** and WJST, even if the functional H_{ecc} to Q_{conc} ratio
309 increased in **BMSJT** but not in WJST.

310

311 The specific WJST vs **BMSJT** training-induced adaptations in *vastus lateralis* muscle architecture
312 is introduced here for the first time. The greater increases in fascicle length after WJST than in
313 **BMSJT** may derive from the enhanced eccentric phase due to the greater external load used in
314 WJST. Such a hypothesis is in agreement with the studies that have reported eccentric-only (11,20)
315 or enhanced eccentric training-induced (32) fascicle elongations. Indeed, as debated in the
316 literature, it seems that eccentric exercise selectively affects fascicle length (1,11,20). Increments in
317 fascicle length are reflective of serial sarcomere addition, which facilitates fastening in muscle
318 contraction and larger range of movements (5). Consistently, combined jump/sprint training was
319 able to induce *vastus lateralis* fascicle elongation, **in both distal and proximal sites by a large**
320 **extent** (4). On the other hand, increases in pennation angle do not seem to be induced after
321 enhanced eccentric training. The present data highlighted that only **BMSJT increased pennation**
322 **angle, indicating that a greater eccentric work does not usually affect the in-parallel**
323 **sarcomere number and consequent increases in pennation angle** (1,11,20). Similarly to the
324 present study, increases in pennation angle were reported after **body mass jump** training (15).

325

326 On the contrary decreases in pennation angle occurred after combined jump/sprint training (4).
327 Since inhomogeneous changes in *vastus lateralis* muscle architecture were reported (4,18), the lack
328 of changes in WJST may have derived from the different sites on which the ultrasound scans were
329 placed. Lastly, adaptations in muscle thickness can depend on adaptations in pennation angle,
330 fascicle length, or both. The *small* and *moderate* increases (for WJST and **BMSJT**, respectively) in
331 *vastus lateralis* muscle thickness are in contrast with previous studies that failed to show changes in
332 muscle thickness after a **jump-squat training performed at the load that elicited optimum**
333 **power (15)** or combined **body mass** jump/sprint training (4). One possible explanation for such an
334 inconsistency may be the different populations involved. Both the above-mentioned studies
335 recruited competitive athletes (4) or resistance-trained men (15), while the present population
336 consisted of recreational soccer players. Given the greater training-induced effectiveness in
337 structural muscle adaptations in untrained vs trained populations (22), it may be hypothesized that
338 the current participants were more prone to muscle enlargements. **However, since the current**
339 **increases in muscle thickness had *small* or *moderate* extent, it should be acknowledged that**
340 **the traditional strength training could be more effective, as previously reported (4,15).** Aside,
341 greater increases in **lower-limb** LM were found in WJST than in **BMSJT**, although both
342 increments were *small*. Increases in muscle size were previously reported (4), and they were shown
343 to be specifically related to type-IIx fibres (40). The present results agree with a previous study that
344 reported greater hypertrophy after eccentric vs traditional training (13). On the contrary, no change
345 in LM occurred in resistance-trained males (15), suggesting that the different initial fitness level
346 may have led to different adaptations.

347
348 *Very large* improvements in agility T-test time occurred only in WJST, with no changes recorded in
349 **BMSJT**. The present results are in line with a previous study reporting improvements in COD after
350 jump-squat training with the optimum power load (27). Consistently, jump-squat training added to
351 traditional strength training resulted in gains in COD, as previously reported (23).

352 COD requires the athletes to rapidly brake and immediately accelerate their body in different
353 directions. The greater external load in WJST than in **BMSJT** may have conditioned the
354 participants to effectively perform both decelerations and accelerations required by the intervention
355 (27). The increased capacity to rapidly accelerate the body mass is a key-feature for sprint
356 performance (39). The present results confirmed the effectiveness of WJST in improving sprint
357 performance (15,39), as well as combined jump/sprint training (4) or strength/jump training (23).
358 **Unloaded jumps** resulted in greater force at a given velocity within the force/velocity relationship
359 (16). This may lead to argue that training with no external load may reduce transfer in power from
360 training to performance. Such a transfer depends on the training intensity, frequency as well as
361 specificity, as previously reported (15). In addition, it may be expected that recreational soccer
362 players may be accustomed to both sprint and CODs (8). Therefore, the absence of further
363 improvements in **BMSJT** may be explained by the insufficient stimuli received during the training.
364 Lastly, the greater eccentric load that WJST underwent may have greatly accounted for the
365 increases in concentric/eccentric tasks as **demand** in COD and sprints, as previously shown (17).
366 Notwithstanding the greater external load in WJST, greater increases in SJ and CMJ were recorded
367 in **BMSJT**. The increases in jump height after **jump** training have been largely reported (4,15–
368 17,30,39). However, the training-testing specificity may have played a key-role in the greater
369 improvements in **BMSJT**, since both training and testing were performed without any external
370 load. **In line with the current result, adding an eccentric overload exercise did not lead to any**
371 **difference in jump height gained compared to traditional training in handball players** (33). In
372 addition, it may be argued that **BMSJT** could have accustomed the participants to higher velocities
373 developed during the vertical jumps, resulting in greater specific jumping adaptations (27).
374
375 To the best of the authors' knowledge, another novel aspect of the present investigation is the
376 selective increment in functional H_{ecc} to Q_{conc} ratio in **BMSJT** but not in WJST.
377

378 The functional H_{ecc} to Q_{conc} ratio can be used to evaluate the hamstrings strain-injury risk, as the
379 lower the ratio, the higher the risk (9). The different outcomes shown in **BMSJT** vs WJST are
380 mainly due to the greater, albeit not different, increases in quadriceps concentric peak-torque in
381 WJST than in **BMSJT**, with very similar increases in hamstrings eccentric peak-torque. It could be
382 speculated that the loaded jumps led to greater trunk flexion in order to maximize the jump height
383 (2). Thus, higher forward load may have differently stimulated **the** forward vs backward **lower-**
384 **limb** muscles. The increases in squat 1-RM and quadriceps and hamstrings peak-torque come with
385 previous inconsistent literature. Indeed, no improvement in squat 1-RM (15) or quadriceps
386 concentric peak-torque (4) was observed after jump-squat training. Conversely, increases in half
387 squat 1-RM (40) or in isometric maximal force (38) were previously reported. It can be argued that
388 the current unaccustomed participants may have resulted in **small but significant** strength gains.
389 Aside, the similar between-group adaptations in lower-limb muscles strength may derive from the
390 similar total training load volume, as already shown (11,13). **Particularly, WJST resulted in**
391 **overall greater but not significant increases in quadriceps strength, irrespective of the testing**
392 **modality. In line with the present results, it was shown that volume-matched eccentric isoload**
393 **vs isokinetic training resulted in similar knee-extensors strength gains (11). Interestingly,**
394 **volume-matched but different training modalities resulted in similar increases in bench press**
395 **1-RM (13).**

396
397 The present investigation comes with some acknowledged limitations and some interesting
398 perspectives. Firstly, the unaccustomed population may have been sensitive to the training-induced
399 adaptations. Therefore, further accustomed populations should be included for a more
400 comprehensive evaluation of the jump-squat training-induced adaptations. Secondly, the present
401 investigation has been conducted off-season. This may permit to isolate its training-induced
402 adaptations, but it should be tailored to the weekly training load when performed pre- or in-season.

403

404 Thirdly, only the traditional lower and upper bounds of the external load that maximizes power
405 were here examined. Therefore, further loads in between could provide more insights on this topic.
406 Lastly, power output was not measured during the training or during the SJ and CMJ. **The lack of**
407 **the power measurement did not allow the correct use of the training load that elicits the**
408 **maximum power.** However, the present investigation was designed to have a strong practical
409 impact, **since the device necessary to measure power output is often unavailable in the field**
410 **practice.**

411
412 In conclusion, specific training-induced adaptations were observed after **BMSJT** or WJST. Despite
413 similar increases in *vastus lateralis* muscle thickness, greater increases in fascicle length occurred
414 in WJST, while increases in pennation angle occurred only in **BMSJT**. In addition, greater
415 increases in LM were shown in WJST than in **BMSJT**. Specific load-dependent performance
416 improvements were shown, as COD and sprint performance improved only in WJST, while greater
417 increases in jump height were observed in **BMSJT**. Such adaptations were accompanied by similar
418 increases in quadriceps and hamstrings strength and by increases in functional H_{ecc} to Q_{conc} ratio in
419 **BMSJT** but not in WJST.

420

421 **PRACTICAL APPLICATIONS**

422 The present findings suggest that different external loads should be used to selectively improve
423 COD, sprint or jump performance in recreational soccer players. Since the increased role of COD in
424 soccer (8), trainers and conditioners may use WJST to improve such an ability. Similarly, the same
425 training method may be recommended to improve sprints, while weight-free jump-squats should be
426 proposed to improve jumping ability.

427 The functional H_{ecc} to Q_{conc} ratio is often monitored to reduce the hamstrings strain injury risk.
428 Since it was seen to decrease with the advancement of a soccer match (9), specific training sessions
429 should be dedicated to **reinforce hamstrings eccentric strength.**

430 Although specific exercises have been proposed (e.g., Nordic hamstrings) (6), it can be suggested
431 here **that BMSJT could be included into a weekly routine, possible coupled with specific**
432 **hamstrings lengthening exercises, since the *small* effect here reported.**

433

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Table 1: Mean values (SD) of quadriceps' muscle architecture and lower-limbs fat-free mass pre- and post- training are shown. Changes (%) and effect size are reported with confidence interval (CI95%).

	Pre: Mean (SD)	Post: Mean (SD)	Change (%) (CI95%)	Effect size (CI95%)
Muscle thickness (mm)				
BMSJT	24.9(3.4)	28.0(3.6)	12 (7 to 18)	0.89 (0.53 to 1.25)
WJST	23.7(3.8)	25.6(2.6)	8 (3 to 14)	0.45 (0.12 to 0.79)
CON	25.5(3.2)	26.1(3.8)	2 (-5 to 7)	0.14 (-0.02 to 0.26)
Pennation angle (°)				
BMSJT	14.5(2.7)	17.7(3.5)	18 (10 to 26) #	1.03 (0.78 to 1.29)
WJST	15.2(3.3)	16.1(3.5)	6 (-2 to 14)	0.26 (-0.10 to 0.62)
CON	14.1(2.2)	14.3(3.6)	1 (-7 to 9)	0.06 (-0.25 to 0.37)
Fascicle length (mm)				
BMSJT	94(10)	100(12)	6 (1 to 11)	0.54 (0.40 to 0.68)
WJST	95(12)	108(10)	10 (4 to 16) *	1.18 (0.82 to 1.54)
CON	98(15)	100(14)	2 (-5 to 9)	0.14 (-0.10 to 0.34)
Fat-free mass (Kg)				
BMSJT	21.6(2.2)	22.1(2.1)	2 (4 to 6)	0.21 (0.07 to 0.37)
WJST	21.1(2.3)	22.2(2.3)	5 (3 to 7) *	0.44 (0.29 to 0.59)
CON	22.2(2.2)	22.1(2.0)	0 (-2 to 2)	-0.01 (-0.10 to 0.10)

BMSJT: body mass squat jump training; **WJST**: weighted jump-squat training.

* : greater than **BMSJT**; # : greater than **WJST**

Table 2: Mean values (SD) of performances in COD, sprinting and jumping pre- and post-training are shown. Changes (%) and effect size are reported with confidence interval (CI95%).

	Pre: Mean (SD)	Post: Mean (SD)	Change (%) (CI95%)	Effect size (CI95%)
Agility T-test (s)				
BMSJT	15.2(0.9)	15.2(0.8)	0 (-2 to 2)	-0.04 (-0.28 to 0.20)
WJST	15.4(0.5)	13.9(0.5)	-10 (-12 to -7) *	-2.95 (-3.18 to -2.72)
CON	15.4(0.9)	15.5(0.6)	1 (-1 to 3)	0.16 (-0.09 to 0.41)
10 m sprint (s)				
BMSJT	1.9(0.1)	1.9(0.1)	0 (-3 to 3)	0.10 (-0.30 to 0.40)
WJST	2.0(0.2)	1.8(0.2)	-5 (-8 to -2) *	-0.52 (-0.82 to 0.22)
CON	1.8(0.1)	1.9(0.1)	2 (-1 to 5)	0.04 (-0.30 to 0.39)
30 m sprint (s)				
BMSJT	4.4(0.2)	4.4(0.2)	-2 (-10 to 8)	-0.06 (-0.33 to 0.43)
WJST	4.6(0.2)	4.4(0.2)	-6 (-9 to -3) *	-0.52 (-0.81 to -0.23)
CON	4.5(0.2)	4.5(0.2)	-1 (-8 to 6)	-0.04 (-0.30 to 0.39)
SJ (cm)				
BMSJT	38.8(3.3)	41.8(5.0)	8 (4 to 13) #	0.89 (0.43 to 1.35)
WJST	38.6(5.7)	40.4(4.9)	5 (0 to 9)	0.30 (0.03 to 0.58)
CON	39.2(5.6)	39.5(5.0)	0 (-4 to 5)	0.02 (-0.27 to 0.31)
CMJ (cm)				
BMSJT	40.8(6.9)	44.6(6.2)	10 (6 to 14) #	0.55 (0.37 to 0.73)
WJST	40.4(6.4)	42.2(6.6)	5 (1 to 9)	0.28 (0.08 to 0.48)
CON	40.5(4.7)	41.1(5.1)	1 (-2 to 5)	0.10 (-0.18 to 0.38)

BMSJT: body mass squat jump training; **WJST**: weighted jump-squat training.

SJ: Squat jump; **CMJ**: counter-movement jump.

* : greater than **BMSJT**; # : greater than **WJST**

Table 3: Mean values (SD) of quadriceps' and hamstrings' strength pre- and post-training are shown. Changes (%) and effect size are reported with confidence interval (CI95%).

	Pre: Mean (SD)	Post: Mean (SD)	Change (%) (CI95%)	Effect size (CI95%)
Squat 1-RM (Kg·BM⁻¹)				
BMSJT	1.21(0.20)	1.30(0.22)	7 (2 to 12)	0.40 (0.15 to 0.75)
WJST	1.18(0.14)	1.33(0.21)	13 (6 to 20)	0.73 (0.34 to 1.07)
CON	1.19(0.23)	1.21(0.23)	1 (-10 to 12)	0.05 (-0.20 to 0.30)
Quadriceps CPT (N·m)				
BMSJT	226(39)	249(41)	10 (5 to 15)	0.58(0.30 to 0.85)
WJST	214(34)	248(37)	16 (10 to 22)	0.97(0.65 to 1.29)
CON	223(40)	222(41)	0 (-9 to 10)	-0.01(-0.13 to 0.12)
Quadriceps EPT (N·m)				
BMSJT	284(45)	324(41)	15 (9 to 21)	0.88 (0.49 to 1.26)
WJST	274(46)	341(65)	24 (18 to 31)	1.46 (1.07 to 1.89)
CON	295(60)	300(67)	2 (-11 to 13)	0.05 (-0.15 to 0.25)
Hamstrings EPT (N·m)				
BMSJT	195(35)	230(46)	17 (10 to 24)	0.98 (0.65 to 1.31)
WJST	190(29)	220(34)	15 (9 to 21)	0.94 (0.60 to 1.28)
CON	199(38)	204(43)	2 (-4 to 8)	0.08 (-0.10 to 0.26)
Functional Ratio (A.U.)				
BMSJT	0.86(0.12)	0.92(0.14)	7 (4 to 10) #	0.51 (0.32 to 0.70)
WJST	0.88(0.13)	0.88(0.15)	1 (-5 to 7)	0.08 (-0.43 to 0.64)
CON	0.89(0.12)	0.91(0.14)	3 (-6 to 11)	0.24 (-0.10 to 0.48)

BMSJT: body mass squat jump training; **WJST**: weighted jump-squat training.
 BM: body mass; CPT: concentric peak-torque; EPT: eccentric peak-torque.
 #: greater than WJST