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1 **Lower trapezius weakness and shoulder complex biomechanics during the tennis serve**

2 Gillet Benoit^{1,2}, Rogowski Isabelle¹, Monga-Dubreuil Elodie², and Begon Mickaël^{2,3}.

3 ¹ Univ Lyon, University Claude Bernard Lyon1, Interuniversity Laboratory of Locomotion
4 Biology – EA 7424, UFRSTAPS 27-29 Boulevard du 11 novembre 1918, 69622 Villeurbanne
5 Cedex, France

6 ² Laboratory of Simulation and Movement Modeling (S2M), School of Kinesiology and
7 Science of Physical Activity, Faculty of Medicine, University of Montréal, Montreal, Quebec,
8 Canada

9 ³ Research center of the CHU SAINTE-JUSTINE Mother and child university hospital center,
10 Montréal, Quebec, Canada

11 Corresponding author:

12 Isabelle Rogowski

13 UCB Lyon 1 – UFRSTAPS

14 27-29, bd du 11 novembre 1918

15 69622 Villeurbanne Cedex France

16 E-mail: isabelle.rogowski@univ-lyon1.fr

17

18 **Abstract:**

19 **PURPOSE:** This study aimed to assess the effect of lower trapezius (LT) weakness on humeral
20 and scapular kinematics and shoulder muscle activity during the tennis serve. **METHODS:**
21 Fifteen competitive male tennis players (age: 23.8 ± 3.4 years; height: 182.8 ± 6.7 cm; mass:
22 76.6 ± 8.7 kg; tennis experience: 15.6 ± 4.9 years) performed two tennis serves before and after
23 selective fatigue of the LT (25-min electric muscle stimulation). During each tennis serve,
24 racket, humeral and scapular kinematics and the activity of 13 shoulder muscles were recorded
25 using an optoelectronic system synchronized with indwelling and surface electromyography.
26 The serve was split into five phases, i.e., early and late cocking, acceleration, early and late
27 follow-through. **RESULTS:** Selective fatigue led to a $22.5 \pm 10.4\%$ strength decrease but did
28 not alter maximum racket speed and humerothoracic joint kinematics. However, increased
29 scapular upward rotation was observed in the acceleration ($p=0.02$) and early follow-through
30 ($p=0.01$) phases. Decreased muscular activity was observed during the early cocking phase for
31 the LT ($p=0.01$), during the acceleration phase for the LT ($p=0.01$), anterior deltoid ($p=0.03$),
32 pectoralis major ($p=0.04$) and subscapularis ($p=0.03$), and during the early follow-through
33 phase for the anterior deltoid ($p=0.03$) and LT ($p=0.04$). **CONCLUSION:** LT weakness altered
34 neither serve velocity nor humerothoracic joint kinematics, but impaired scapulothoracic
35 kinematics and anterior shoulder muscle activation. Such alterations may reduce the
36 subacromial space and jeopardize humeral head stability. These findings shed new light on the
37 consequences of LT weakness, highlighting the importance of monitoring and strengthening
38 this muscle in overhead athletes.

39 Key words: overhead sport, muscle activity, humerothoracic joint, scapulothoracic joint

41 **Introduction**

42 Chronic shoulder injuries affect 20 to 50% of both junior and adult tennis players (1, 2). These
43 injuries commonly involve scapular dyskinesis, which is an alteration of the physiological
44 movement or positioning of the scapula (3). Causes of scapular dyskinesis include nerve palsy
45 (long thoracic and spinal accessory), muscle stiffness (pectoralis minor, biceps sort head),
46 glenohumeral internal rotation deficit related to tightness of the posterior soft tissues, or
47 alterations in the periscapular muscles (3). However, it is weakness, fatigue or delay in
48 activation of the lower trapezius muscle (LT) that are thought to be the primary causes of
49 scapular dyskinesis (3). Yet exactly how such LT alterations affect tennis skills remains unclear.
50 Fatigue is defined as a physiological process that decreases the muscle's ability to produce force
51 and alters its contraction timing (4). Most fatigue studies use a specific task to target one muscle
52 or one muscle group (5, 6). However, such tasks also fatigue the surrounding muscles, due to
53 co-contraction and synergistic processes, as well as the other muscles involved in the kinetic
54 chain (7). To better target one single muscle, therefore, electric muscle stimulation is often used
55 (8, 9). With the electrodes placed close to the muscle tendons, the stimulation acts on the
56 intramuscular axons triggering the contraction (10). The high metabolic demand from such
57 contractions leads to peripheral fatigue, thereby reducing the muscle's ability to produce force
58 (10). Electric muscle stimulation can be considered an appropriate way to produce muscle
59 weakness and thus to observe its impact on tennis skills.

60 The tennis serve is the most frequent stroke during a game, representing 45 to 60% of all strokes
61 (11). During the cocking phase of the tennis serve, the LT acts concentrically to posteriorly tilt
62 and externally rotate the scapula, (7, 12), while the humerus is abducted to 90° and at maximum
63 external rotation (12). During the follow-through phase, the LT also acts eccentrically to
64 restrain scapular anterior tilt and internal rotation (7, 12). In addition, the tennis serve is known
65 to engender a high risk of shoulder injury because of: (i) the physiological contact between the

66 greater tuberosity of the humeral head and the posterosuperior part of the scapular glenoid at
67 the end of the cocking phase (13, 14); and (ii) the high constraint applied to stabilize the
68 shoulder complex when upper-limb/racket motion is decelerated, *i.e.* during the follow-through
69 phase (15). It has been shown that overhead athletes with an impingement sign present
70 decreased LT activation and increased upper trapezius activation (16, 17). Such intramuscular
71 imbalance may limit scapular external rotation and posterior tilt (3, 17). Performing a tennis
72 serve with a weak LT may thus affect scapular kinematics, potentially resulting in increased
73 pressure on the tuberosity-glenoid contact (18) and anterior translation of the humeral head
74 (12). However, to the best of our knowledge, the effect of LT weakness on shoulder complex
75 biomechanics during the tennis serve has never been studied. Knowledge of such biomechanical
76 effects could shed light on shoulder pathomechanics as related to LT weakness, suggesting
77 strategies to improve injury prevention in tennis.

78 This study aimed to assess the influence of LT weakness on humeral and scapular kinematics
79 and on shoulder muscle activity during a tennis serve. We hypothesized that decreased LT
80 strength (caused by selective fatigue) would be compensated for by increased upper trapezius
81 activity. As the LT is mainly involved in the cocking and follow-through phases, this change in
82 the upper-lower trapezius force couple would result in altered scapular internal/external rotation
83 and anterior/posterior tilt during both phases.

84

85 **Methods**

86 *Participants*

87 Fifteen competitive male tennis players (age: 23.8 ± 3.4 years; height: 182.8 ± 6.7 cm; mass:
88 76.6 ± 8.7 kg; tennis experience: 15.6 ± 4.9 years; weekly tennis training: 4.4 ± 1.8 hours,
89 Canadian ranking: 4 to 6; International Tennis Number: 2 to 4 according to the system of
90 equivalent rankings of the International Tennis Federation) gave their written informed consent

91 to participate in this study, which was approved by the ethics committee of the 'Université de
92 Montréal' (16-165-CERES-D). Inclusion criteria were being an adult competitive player with
93 an International Tennis Number rating better than 6. Exclusion criteria were having shoulder
94 problems in the last six months or heart problems.

95

96 *Experimental design*

97 The experiment was structured in two sessions scheduled at least 48h apart to allow full
98 recovery: 1) familiarization with electric muscle stimulation on the dominant LT to determine
99 the maximum intensity of the fatigue task that the player could tolerate and 2) testing. During
100 the testing session, participants performed two sets of 13 maximum voluntary isometric
101 contractions (MVIC), a static position, a series of setup trials (included a static position with
102 the arm abducted to 90° in the scapular plane and with the arm fully abducted, lateral tilt of the
103 trunk, rotation of the trunk, flexion/extension of the trunk, flexion/extension of the elbow,
104 pronation/supination of the forearm, rotation of the wrist, flexion/extension of the wrist and
105 abduction/adduction of the wrist) to locate the joint centers. They performed two set of two
106 tennis serves. Before a first set of two serves, players performed a 10-15 min warm-up in line
107 with their own routine. To familiarize them with the study conditions, they also repeated a few
108 racket strokes in the camera field of view (width: 4 m, length: 5 m; height: 3 m). Players then
109 performed the fatigue task targeting their dominant LT, and immediately afterwards performed
110 a second set of two tennis serves. Two tennis serves ensure a short delay between the end of the
111 electrostimulation period and the end of motions of interest to limit the recovery of lower
112 trapezius strength.

113

114 *Kinematics*

115 Players were equipped with 33 reflective skin markers (pelvis: 4; thorax: 6; clavicle: 2; scapula:
116 5; arm: 4; forearm: 4; wrist: 4; hand: 4) according to Jackson et al.'s (19) kinematics model
117 (Figure 1). In line with the findings of Blache, Dumas, Lundberg and Begon (20) about shoulder
118 soft tissue artefact, the most affected markers of the Jackson et al.'s (19) kinematics model were
119 removed to simplify the model. This marker set included anatomical markers positioned on
120 bony landmarks to define the biomechanical model and technical markers positioned on skin
121 areas that minimize soft tissue artifacts. Six additional markers were attached to the racket-head
122 and one marker to the non-dominant hand, to determine performance and the beginning of the
123 serve motion, respectively. The reflective marker positions were recorded by an 18-camera
124 motion analysis system (VICON T20S & T40S, Oxford, UK) at 300 Hz during static position
125 and tennis serves. Before and after selective fatigue of the dominant LT, participants performed
126 two flat serves without a ball (for in-lab safety reasons) at maximum speed, having been
127 instructed to reproduce the technique they used on the tennis court.

128 A 25 degree-of-freedom (DOF) kinematics model was personalized using the static and setup
129 trials: global-pelvis and thoracopelvic joints (6 DoF each), sternoclavicular and
130 acromioclavicular (3 DoF each), glenohumeral (3 DoF), elbow and wrist (2 DoF each). The
131 centers of rotation of the wrist joint and between the pelvis and the thorax were located using
132 the SCoRE algorithm (21) and elbow flexion and supination axes using the SARA algorithm
133 (22), while the sternoclavicular, acromioclavicular and glenohumeral joint centers were defined
134 according to anatomical bony landmarks (23). Finally, following Michaud et al. (2017), a
135 scapulothoracic pseudo-joint constraint was modeled as a point-to-ellipsoid contact (barycenter
136 of the Angulus Acromialis, Angulus Inferior and Trigonum Spinae) where a thorax-sized
137 ellipsoid was fitted to the area covered by the scapula. Briefly, the ellipsoid radii were obtained
138 by minimizing the sum of the quadratic distances between the scapula landmarks (angulus
139 inferior and trigonum spinae) and the ellipsoid envelope for three arm positions (rest, abducted

140 to 90°, fully abducted). Moreover, the most lateral point of the mediolateral axis of the ellipsoid
141 had to be the most lateral point of the thorax and the origin of center of the ellipsoid had to
142 coincide with the origin of the thorax coordinate system (24).

143 Humerothoracic and scapulothoracic rotation matrices, usually used to determine shoulder
144 kinematics in tennis (12), were calculated from the sternoclavicular, acromioclavicular and
145 glenohumeral joint angles. Then the Cardan angles were extracted to define the joint rotation
146 axes, with X the antero-posterior direction, Y the lateral direction and Z the infero-superior
147 direction. The humerothoracic joint rotations were, successively, abduction(-)/adduction(+),
148 flexion(+)/extension(-) and internal(+)/external(-) rotation, according to the YXZ rotation
149 sequence (25). The scapulothoracic joint rotations were internal(+)/external(-) rotation,
150 upward(-)/downward(+) rotation and anterior(-)/posterior(+) tilt, and were defined using the
151 rotation sequence ZYX (26).

152

153 *Electromyography*

154 Supraspinatus, infraspinatus and subscapularis activities were measured using indwelling
155 electromyography (EMG) sampled at 2000 Hz (Figure 1). Under sterile conditions,
156 intramuscular paired hook-fine-wire electrodes (30 mm x 27 ga, Natus Neurology, Middleton,
157 WI, USA) were inserted according to Kadaba et al. (27) and Morris et al. (28). The activities of
158 the anterior, posterior and middle deltoids, biceps, triceps, pectoralis major, upper and lower
159 trapezius, latissimus dorsi, and the serratus anterior were recorded using surface EMG sampled
160 at 2000 Hz. After shaving and cleaning the skin with alcohol, sensors (Delsys Trigno Wireless
161 EMG, Natick, MA, USA; inter-electrode distance of 10 mm) were placed according to the
162 SENIAM recommendations over the muscle belly (Figure 1). Thirteen maximum voluntary
163 isometric contractions (MVIC) were performed to assess the maximum voluntary activation of
164 each muscle (29). Participants performed two 5-s contractions for each MVIC with 30 s rest

165 between contractions. The raw EMG signal was filtered using a 4th order Butterworth bandpass
166 filter (15- 500 Hz for the surface EMG and 15- 800 Hz for the indwelling EMG). The EMG
167 envelope values were calculated using a 250-ms sliding window Root Mean Square for the
168 MVIC and a 50-ms sliding window for the serve. For each muscle, the envelopes were
169 normalized by the maximum muscle voluntary activation obtained over the two repetitions of
170 13 MVIC tests (29). The envelope of every muscle was integrated (iEMG) over the different
171 phase durations (i.e., early and late cocking, acceleration and early and late follow-through; see
172 section *serve analysis*) for statistical analysis.

173  Insert Figure 1

174

175 *Fatigue Task*

176 The fatigue task was performed after the first set of serves. A musculoskeletal electric
177 stimulator (Compex mi-Sport; DJO Global, Vista, CA) was used to generate a decrease in LT
178 strength due to peripheral fatigue. Participants were in a supine position, humerus abducted to
179 140° and at maximum external rotation. Bipolar electrodes (5 cm x 5 cm) were placed on the
180 skin over the extremities of the LT, close to the lateral side of the seventh thoracic spinous
181 process and close to the medial part of the inferior angle of the scapula, in line with Bdaiwi et
182 al. (9). The current width pulse was 300 μ s, and the frequency was 40 Hz. The session lasted
183 25 minutes. Current intensity was increased every two minutes during the first half of the
184 session. Once the maximum intensity determined as tolerable for the players from the first
185 session was reached, current intensity was kept constant. Mean intensity was 79.5 ± 60.5 mA
186 (range: 48 to 120 mA). To monitor strength decrease, players performed a one-repetition lower
187 trapezius isometric strength test (30) before and immediately after the fatigue task, and after the
188 second set of serves. For the strength tests, players were in a supine position, humerus abducted
189 to 140° and at maximum external rotation, with elbow fully extended. Strength was measured

190 using a hand-held dynamometer (HHD; microFET2; Hoggan Health Industries Inc, West
191 Jordan, Utah, USA) placed on the lateral aspect of the distal radius while the players exerted
192 extension against the resistance of the experimenter.

193

194 *Serve analysis*

195 The barycenter of the six markers of the racket-head, coinciding with its center, was computed
196 and used to calculate racket-head velocity throughout the tennis serve. The pre-impact
197 maximum velocity of each serve was defined as the performance factor (31). Four key events
198 in the tennis serve were determined based on joint kinematics: 1) the beginning of the
199 movement, corresponding to the time when the non-dominant hand was at the same height as
200 the xiphoid process; 2) the end of the cocking phase, defined as the maximum humeral external
201 rotation; 3) the impact ($T_{\text{impact}}=0$ s), defined as the maximum racket elevation (15); and 4) the
202 end of the movement, corresponding to the minimum humeral adduction (12). The
203 humerothoracic and scapulothoracic joint rotations at each key event were collected for
204 subsequent analysis. According to these four events, three phases were defined: the cocking
205 phase from the beginning of the movement to the maximum humeral external rotation, the
206 acceleration phase from the maximum humeral external rotation to the impact, and the follow-
207 through phase from the impact to the end of the movement. The cocking and follow-through
208 phases were also divided into two subphases as proposed by Morris, Jobe, Perry, Pink and Healy
209 (32): early (0-75%) and late (75-100%) cocking; early (0-25%) and late (25-100%) follow-
210 through. Overall, therefore, the tennis serve was divided into 5 phases according to 6 events (4
211 key events and the 2 subordinate events). For each phase, duration, iEMG, minimum and
212 maximum humerothoracic and scapulothoracic joint rotations and the timing of these extreme
213 rotations were calculated and used for data analysis.

214

215 *Data reduction*

216 Data for two players were removed from the analysis because some EMG signal recordings
217 failed after the fatigue task. In the end, data for 13 players were used in the analysis, which
218 included 11 players monitored with indwelling EMG (two players did not agree to it).

219

220 *Statistical analysis*

221 After testing the normality and homoscedasticity of the values, paired t-tests were applied to
222 compare outcome measures before and after selective fatigue of the lower trapezius. The effect
223 size (ES) was calculated and interpreted according to the Cohen scale (1988) (33) (small: 0.2,
224 medium: 0.5, and large: 0.8), and level of significance was set at $p \leq 0.05$. All statistical analyses
225 were performed using SPSS 11.0 software (SPSS, Inc., Chicago, IL, USA).

226

227 **Results**

228 The paired t-test showed a significant decrease in LT strength values (Table 1), of $22.5 \pm 10.4\%$,
229 after electric muscle stimulation (ES = 1.26, large effect; $p = 0.001$). After the second set of
230 serves, the decrease in LT strength was $4.0 \pm 15.2\%$, not significantly different from the initial
231 value. No significant differences were found for serve duration and performance (Table 1)
232 before and after LT selective fatigue.

233

234

Insert Table 1

235

236 A representative participant's humerothoracic and scapulothoracic joint kinematics during the
237 tennis serve, before and after selective fatigue of the lower trapezius, are available in
238 Supplemental Digital Content 1 (see Figure, SDC 1, humerothoracic and scapulothoracic joint
239 kinematics during the tennis serve). Angle values at the key events can be found in

240 Supplemental Digital Content 2 (see Table, SDC 2, humerothoracic and scapulothoracic angles
241 at tennis serve key events). At impact, the humerus relative to the thorax was more flexed (ES
242 = 0.63, medium-to-large effect; $p = 0.02$) after the fatigue task (Figure 2). At the end of motion,
243 the humerus relative to the thorax was less internally rotated (ES = 0.71, medium-to-large
244 effect; $p = 0.01$), while the scapula relative to the thorax was more downwardly rotated (ES =
245 0.71, medium-to-large effect; $p = 0.01$) after the fatigue task. No other significant differences
246 were found for humerothoracic and scapulothoracic joint rotations at the tennis serve key events
247 (Figure 2, Supplemental Digital Content 2). The extreme values for shoulder joint kinematics
248 (Table 2) were affected following the fatigue task. The humerus relative to the thorax was
249 significantly more flexed during the acceleration (ES = 0.60, medium-to-large effect; $p = 0.03$)
250 and early follow-through phases (ES = 0.59, medium; $p = 0.03$), while the scapula relative to
251 the thorax was significantly more upwardly rotated (ES = 0.59, medium effect; $p = 0.02$ and ES
252 = 0.67, medium-to-large effect; $p = 0.01$, respectively). No significant differences were found
253 in the timing of the extreme values for shoulder kinematics (Table 2).

254

255 Insert Figure 2 and Table 2

256

257 A representative participant's EMG signal envelopes during the tennis serve, both before and
258 after LT selective fatigue, are available in Supplemental Digital Content 3 (see Figure, SDC 3,
259 EMG signal envelopes of 13 shoulder muscles during the tennis serve). During the early
260 cocking phase (Figure 3), the iEMG of the LT was significantly lower (ES = 0.53, medium
261 effect; $p = 0.04$), while the biceps was significantly more activated (ES = 0.58 medium effect;
262 $p = 0.04$) after LT selective fatigue. During the late cocking phase (Figure 3), iEMG values
263 decreased significantly for the posterior deltoid (ES = 0.67, medium-to-large effect; $p = 0.04$)
264 and the pectoralis major (ES = 0.64, medium-to-large effect; $p = 0.02$) after LT selective

265 fatigue. During the acceleration phase (Figure 3), iEMG values were significantly lower after
266 LT selective fatigue for the LT (ES = 0.98, large effect; p = 0.01), the latissimus dorsi (ES =
267 0.53, medium effect; p = 0.04), the subscapularis (ES = 0.87, large effect; p = 0.03), the anterior
268 deltoid (ES = 0.62, medium-to-large effect; p = 0.03), the pectoralis major (ES = 0.54, medium
269 effect; p = 0.04), and the triceps (ES = 0.68, medium-to-large effect; p = 0.03). During the early
270 follow-through phase (Figure 3), iEMG values were significantly lower after LT selective
271 fatigue for the LT (ES = 0.51, medium effect; p = 0.04), the posterior deltoid (ES = 0.66,
272 medium-to-large effect; p = 0.04), the anterior deltoid (ES = 0.63, medium-to-large effect; p =
273 0.03), the biceps (ES = 0.82, large effect; p=0.01), and the triceps (ES = 0.68, medium-to-large
274 effect; p = 0.03). No differences were found for the other muscles.

275

276

Insert Figure 3 here

277

278 **Discussion**

279 The aim of this study was to investigate whether LT weakness generated by electric muscle
280 stimulation affected scapular and humeral kinematics and shoulder muscle activity during the
281 tennis serve. We found that LT weakness did not alter serve performance, humerothoracic and
282 scapulothoracic joint rotations at the key events, nor humerothoracic joint kinematics during
283 motion. However, weakness decreased LT activation, thereby altering scapulothoracic joint
284 kinematics and leading to a decrease in anterior shoulder muscle activation during the
285 acceleration and follow-through phases.

286 The maximum racket speed of competitive tennis players when serving can be close to 80 km/h
287 (31). In the laboratory, without a ball, our competitive players served at a similar racket speed
288 (85±4 km/h). Our first set of tennis serves presented humeral and scapular kinematics and
289 electromyographic patterns (Figure 2, Figure 3, and Figure A1) similar to those described in

290 the literature. During the cocking phase, the infraspinatus and the posterior deltoid acted to
291 externally rotate the humerus to 125°, while the supraspinatus and middle deltoid acted to
292 abduct the humerus to 100° (7, 12, 34). At the same time, the scapula was slightly externally
293 rotated, upwardly rotated to 30° and posteriorly tilted due to the actions of the serratus anterior,
294 upper and lower trapezii (7, 12, 34). During the acceleration phase, the pectoralis major,
295 latissimus dorsi, and subscapularis muscles were activated to internally rotate the humerus (7,
296 12, 34). The serratus anterior was also activated to internally rotate the scapula to 33° (7, 12,
297 34). The other shoulder muscles acted to stabilize the shoulder joints (7). Finally, during the
298 early follow-through phase, the shoulder muscles continued their activations to internally rotate
299 and adduct the humerus as well as to internally and downwardly rotate and posteriorly tilt the
300 scapula (7, 12). As the laboratory conditions did not seem to significantly influence tennis serve
301 performance and kinematics (35), our serves before LT selective fatigue can be considered an
302 adequate representation of the serve in competitive tennis players. We therefore assume that
303 the alterations in humeral and scapular kinematics and shoulder muscle activity observed after
304 the fatigue task were due to the LT weakness it induced.

305 LT weakness is the principal cause of scapular dyskinesia, commonly involved in shoulder
306 injuries (3, 17). The weakness of a single muscle can be simulated using selective fatigue, which
307 reduces the targeted muscle's ability to produce strength (4, 8). After electric muscle
308 stimulation, we observed a decrease in LT strength of $22.5 \pm 10.4\%$ which was reduced to 4.0
309 $\pm 15.2\%$ after the second set of serves. This large intersubject variability could be explained by
310 the range of electrostimulation current intensities, which were determined according to each
311 players' discomfort tolerance. Participants' recovery in LT strength was almost complete after
312 the post-test (i.e. about 5 min after the fatigue task), as already reported after high intensity
313 exercises (36). The electrostimulation commonly simulates the muscular effort of a high
314 intensity exercise, but the motor unit recruitment differs from a natural contraction (10).

315 Indeed, with the electrostimulation, the motor unit recruitment is randomized, superficial and
316 fixed, while in the natural contraction, it is organized and adaptive (10). During the post-test,
317 the neuromuscular system may be reorganized by recruiting motor units, which were not
318 involved during the electrostimulation task. This could then explain the fast observed strength
319 recovery. The strength decrease that remained at the end of our post-test was however similar
320 to the 4% decrease reported after a series of overhead performances, such as after a baseball
321 game (99 ± 29 throws) (6). We then considered that the second set of tennis serves, i.e. after
322 electric stimulation, was performed with a weaker LT than the first set.

323 Despite LT weakness, the players sustained their performance and maintained their
324 humerothoracic and scapulothoracic joint rotations during tennis serve key events, as well as
325 their humerothoracic joint kinematics throughout the tennis serve. Previous EMG studies (7,
326 12) showed that during this motion, the LT acts to externally rotate and posteriorly tilt the
327 scapula during the late cocking phase and helps decelerate the arm-racket complex during the
328 follow-through phase by controlling and limiting the internal and upward rotation and anterior
329 tilt of the scapula. In the weakness condition, LT activation was low throughout the tennis serve.
330 A decrease in LT activation is commonly compensated for by an increase in upper trapezius
331 activation during arm abduction or arm rotation (16, 17). However, this adaptation was not
332 observed during the tennis serve: upper trapezius activity was not modified. Decreased LT
333 activation coupled with unchanged upper trapezius activation may alter scapular kinematics
334 (17). We also found increased scapular upward rotation during both the acceleration and the
335 early follow-through phases. According to Ludewig & Reynolds (37), such an increase is
336 thought to be beneficial, increasing the subacromial space when the upper limbs are elevated,
337 as in the acceleration phase. However, according to Karduna et al. (38), it may also reduce the
338 subacromial space when the humerus is abducted to 90° and maximally internally rotated, as in
339 the follow-through phase. Consequently, performing the follow-through phase under LT

340 weakness may place the shoulder at higher risk of rotator cuff tendon impingement between the
341 acromion and the humeral head. Furthermore, in our study, the decrease in LT activation was
342 accompanied by reduced activations of other shoulder muscles: posterior (posterior deltoid and
343 triceps brachialis) and anterior (anterior deltoid, latissimus dorsi, pectoralis major,
344 subscapularis, and biceps brachialis). Since most of these muscles are involved in the humeral
345 head's active stability through their co-contraction (39), their reduced activations could
346 jeopardize humeral head stability, potentially resulting in shoulder impingement (40). With
347 repeated serves during tennis training and competition, the potential decrease in the subacromial
348 space and loss of humeral head stability may increase the risk of rotator cuff tendinopathy (3,
349 18, 38). Consequently, performing repeated serves with a weak LT may alter scapular
350 kinematics and humeral head stability and potentially jeopardize rotator cuff tendon integrity.
351 One limitation to this study is the fact that selective fatigue was induced through electric muscle
352 stimulation, which could trigger non-physiological contractions (10) that may affect muscle
353 functions differently from a physiological contraction. Consequently, the results obtained from
354 simulated LT weakness may differ slightly from those that would be observed with natural LT
355 weakness. Furthermore, the maximum intensity of electrostimulation tolerable by each player
356 was determined after a unique familiarization session, resulting in a large variability in current
357 intensity (48 to 120 mA) used for the fatigue task. This variability may explain the large inter-
358 subject variability observed in LT strength decrease. More familiarization sessions should be
359 included in future studies to determine the maximum intensity tolerable for player with more
360 accuracy. A second limitation concerns the study's lack of clinical assessment of scapular
361 dyskinesia, tendinopathies and impingements, shoulder problems related to LT weakness and
362 which could alter shoulder biomechanics. The test-retest procedure used in this study should
363 minimize the impact of shoulder problems, since each player acted as his own control. Finally,
364 our laboratory conditions meant that the serves were performed without a ball, which may

365 unconsciously influence serve performance. However, this study was the first to assess the
366 effect of LT weakness on humerothoracic and scapulothoracic joint kinematics and shoulder
367 muscle activation during sport-specific motion. It would be valuable to corroborate our results
368 by assessing the shoulder complex kinematics and muscular activity during overhead sport-
369 specific motion in a symptomatic population. Future studies using musculoskeletal modeling
370 may be useful to evaluate the relationship between loss of humeral head stability, change in
371 humeral head translation and LT weakness.

372

373 **Conclusion**

374 Despite the weakness of the lower trapezius, players still achieved a fast tennis serve while
375 maintaining their humeral kinematics. However, they presented a decrease in lower trapezius
376 activation that may alter scapular kinematics and anterior shoulder muscle activation during the
377 acceleration and follow-through phases. Such alteration could reduce the subacromial space
378 and humeral head active stability, hence jeopardizing rotator cuff tendon integrity under
379 intensive competition and training. These findings afford coaches and clinicians insights into
380 the possible shoulder-complex pathomechanics related to weakness in scapular stabilizer
381 muscles. They also underline the importance of monitoring and strengthening the lower
382 trapezius muscle in overhead athletes.

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386

387 **Acknowledgements:**

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389 Explora'doc and Globalink programs, respectively. We are grateful to Yoann Blache,
390 Christophe Hautier, and Benjamin Michaud for their expertise during the data analysis.

391 **Conflict of interest**

392 The authors declare no conflict of interest.

393 The authors also declare that the result of the present study do not constitute endorsement by
394 ACSM

395 The authors declare that the results of the study are presented clearly, honestly, and without
396 fabrication, falsification, or inappropriate data manipulation.

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399 Mitacs with the globalink program.

400

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505 mobility and stability. *J Biomech*. 2007;40(10):2119-29.

507 **Figure caption**

508 Table 1: Mean \pm standard error of maximum isometric strength of the lower trapezius,
 509 duration of serve phases and maximum racket speed before (pre) and after (post) selective
 510 fatigue of the lower trapezius. Significant difference represented in bold.

	Pre	Post	P
Lower trapezius strength (N)	44.8 \pm 4.9	34.3 \pm 3.2	0.001
Duration of the serve (s)	1.28 \pm 0.05	1.24 \pm 0.05	0.07
Duration of the early cocking phase (s)	0.64 \pm 0.03	0.65 \pm 0.03	0.46
Duration of the late cocking phase (s)	0.21 \pm 0.01	0.22 \pm 0.01	0.46
Duration of the acceleration phase (s)	0.09 \pm 0.01	0.08 \pm 0.01	0.11
Duration of the early follow-through phase (s)	0.08 \pm 0.01	0.08 \pm 0.01	0.07
Duration of the late follow-through phase (s)	0.25 \pm 0.02	0.23 \pm 0.02	0.08
Maximum racket speed (km/h)	84.6 \pm 4.2	82.7 \pm 5.1	0.19

511

512

513 Table 2 Mean \pm standard error of the extreme orientations (in degrees) of the humerothoracic (HT) and scapulotohoracic (ST) joints and their
514 timing (in seconds relative to the impact $t_{\text{impact}}=0$ s) in the different tennis phases before (pre) and after (post) selective fatigue of the lower trapezius;
515 bold represents a significant difference before and after fatigue at $p<0.05$.

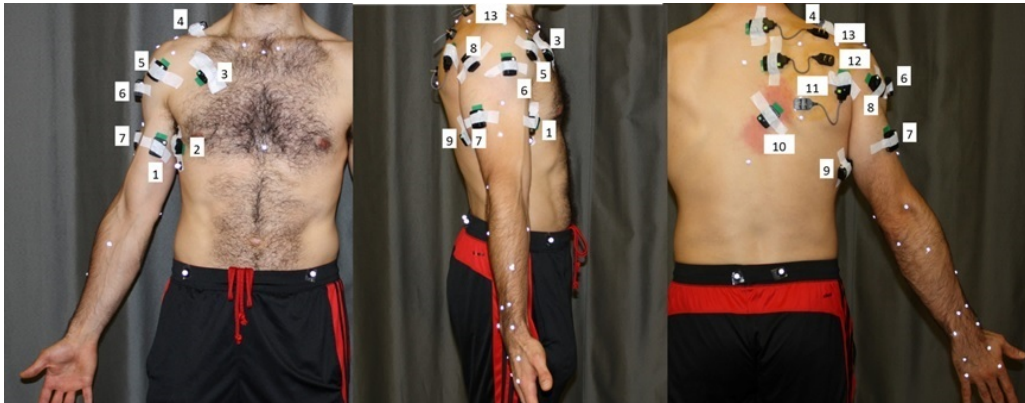
Phases				Maximum	p	timing (s)	p	minimum	p	timing (s)*	p
Late cocking	HT	Abduction(-)/adduction(+)	Pre	-71.8 \pm 4.1	0.41	-0.24 \pm 0.02	0.27	-100.4 \pm 4.5	0.12	-0.12 \pm 0.02	0.48
			Post	-71.5 \pm 4.7		-0.24 \pm 0.01		-98.8 \pm 5.1		-0.12 \pm 0.02	
		Flexion(+)/extension(-)	Pre	36.1 \pm 4.8	0.08	-0.09 \pm 0.01	0.30	0.0 \pm 4.6	0.10	-0.29 \pm 0.01	0.07
			Post	39.3 \pm 4.7		-0.09 \pm 0.01		2.4 \pm 4.3		-0.25 \pm 0.03	
	Internal(+)/external(-) rotation	Pre	-64.1 \pm 4.9	0.21	-0.29 \pm 0.01	0.31	-125.5 \pm 6.8	0.25	-0.09 \pm 0.01	0.12	
		Post	-66.5 \pm 5.9		-0.29 \pm 0.01		-123.9 \pm 6.8		-0.12 \pm 0.03		
	ST	Internal(+)/external(-) rotation	Pre	27.7 \pm 2.9	0.15	-0.13 \pm 0.02	0.13	18.9 \pm 2.7	0.25	-0.23 \pm 0.01	0.49
			Post	29.1 \pm 2.8		-0.11 \pm 0.01		19.3 \pm 2.7		-0.23 \pm 0.02	
		Upward(-)/downward(+) rotation	Pre	-22.8 \pm 4.4	0.47	-0.23 \pm 0.02	0.33	-34.4 \pm 3.2	0.38	-0.16 \pm 0.02	0.16
			Post	-22.9 \pm 4.5		-0.23 \pm 0.02		-34.3 \pm 2.7		-0.14 \pm 0.02	
Anterior(-)/posterior(+) tilt	Pre	5.2 \pm 2.8	0.38	-0.11 \pm 0.01	0.15	-11.7 \pm 2.5	0.25	-0.27 \pm 0.01	0.43		
	Post	4.8 \pm 3.1		-0.10 \pm 0.01		-11.0 \pm 2.4		-0.27 \pm 0.01			
Acceleration	HT	Abduction(-)/adduction(+)	Pre	-88.8 \pm 6.3	0.37	-0.03 \pm 0.01	0.41	-102.7 \pm 4.8	0.22	-0.05 \pm 0.01	0.40
			Post	-87.9 \pm 6.9		-0.03 \pm 0.01		-104.9 \pm 3.9		-0.05 \pm 0.01	
		Flexion(+)/extension(-)	Pre	42.4 \pm 4.7	0.02	-0.02 \pm 0.01	0.47	34.7 \pm 4.9	0.06	-0.06 \pm 0.01	0.32
			Post	45.3 \pm 4.8		-0.02 \pm 0.01		37.8 \pm 4.8		-0.06 \pm 0.01	
	Internal(+)/external(-) rotation	Pre	-72.2 \pm 10.8	0.19	-0.00 \pm 0.00	0.43	-125.5 \pm 6.8	0.24	-0.08 \pm 0.01	0.40	
		Post	-67.6 \pm 12.6		-0.00 \pm 0.00		-123.9 \pm 6.8		-0.09 \pm 0.01		
	ST	Internal(+)/external(-) rotation	Pre	36.5 \pm 2.6	0.30	-0.03 \pm 0.01	0.37	24.8 \pm 2.3	0.13	-0.05 \pm 0.01	0.35
			Post	36.8 \pm 2.6		-0.02 \pm 0.01		26.0 \pm 2.5		-0.06 \pm 0.01	
		Upward(-)/downward(+) rotation	Pre	-24.9 \pm 3.4	0.02	-0.03 \pm 0.01	0.48	-34.9 \pm 2.8	0.42	-0.06 \pm 0.01	0.32
			Post	-27.5 \pm 2.8		-0.03 \pm 0.01		-34.7 \pm 2.6		-0.05 \pm 0.01	
Anterior(-)/posterior(+) tilt	Pre	9.0 \pm 2.7	0.23	-0.04 \pm 0.01	0.28	1.1 \pm 2.8	0.38	-0.06 \pm 0.01	0.38		
	Post	9.4 \pm 2.6		-0.03 \pm 0.01		1.5 \pm 3.1		-0.06 \pm 0.1			
Follow-through	HT	Abduction(-)/adduction(+)	Pre	-71.2 \pm 10.3	0.26	0.06 \pm 0.01	0.37	-98.8 \pm 6.6	0.47	0.03 \pm 0.01	0.35
			Post	-73.7 \pm 9.3		0.06 \pm 0.01		-98.5 \pm 7.1		0.03 \pm 0.01	
		Flexion(+)/extension(-)	Pre	53.0 \pm 3.6	0.16	0.07 \pm 0.01	0.28	36.9 \pm 4.9	0.03	0.02 \pm 0.01	0.47
			Post	55.4 \pm 3.8		0.07 \pm 0.01		41.0 \pm 5.0		0.02 \pm 0.01	
	Internal(+)/external(-) rotation	Pre	19.0 \pm 13.1	0.41	0.08 \pm 0.01	0.43	-72.7 \pm 11.1	0.16	0.00 \pm 0.00	0.38	
		Post	17.1 \pm 10.8		0.08 \pm 0.01		-67.6 \pm 12.6		0.00 \pm 0.00		
	ST		Pre	40.9 \pm 2.4	0.36	0.06 \pm 0.01	0.11	29.2 \pm 2.8	0.33	0.03 \pm 0.01	0.30

Internal(+)/external(-) rotation	Post	41.3 ± 2.6		0.05 ± 0.01		29.6 ± 2.9		0.03 ± 0.01	
Upward(-)/downward(+) rotation	Pre	-18.3 ± 3.5	0.01	0.06 ± 0.01	0.41	-31.4 ± 3.4	0.43	0.02 ± 0.01	0.14
	Post	-21.1 ± 3.4		0.06 ± 0.01		-31.6 ± 3.1		0.02 ± 0.01	
Anterior(-)/posterior(+) tilt	Pre	11.9 ± 3.4	0.30	0.05 ± 0.01	0.13	-0.2 ± 2.9	0.13	0.04 ± 0.01	0.42
	Post	11.3 ± 3.3		0.04 ± 0.01		0.9 ± 2.9		0.04 ± 0.01	

516 Note: * time resolution was 0.003 s.

517

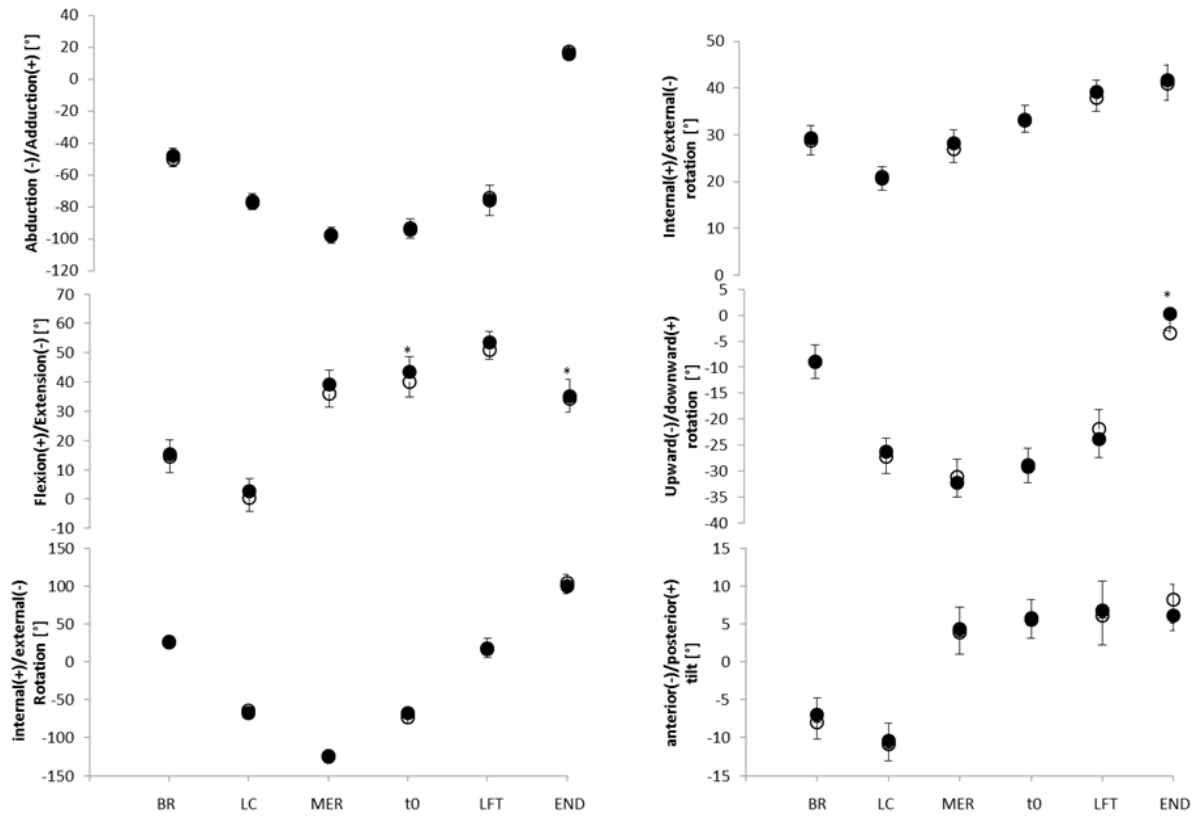
518 Figure 1: Positioning of the 33 reflective markers and the electromyography electrodes with (1)
519 biceps, (2) serratus anterior, (3) major pectoralis, (4) upper trapezius, (5) anterior deltoid, (6)
520 middle deltoid, (7) triceps, (8) posterior deltoid, (9) latissimus dorsi, (10) lower trapezius, (11)
521 subscapularis, (12) infraspinatus, and (13) supraspinatus muscles.



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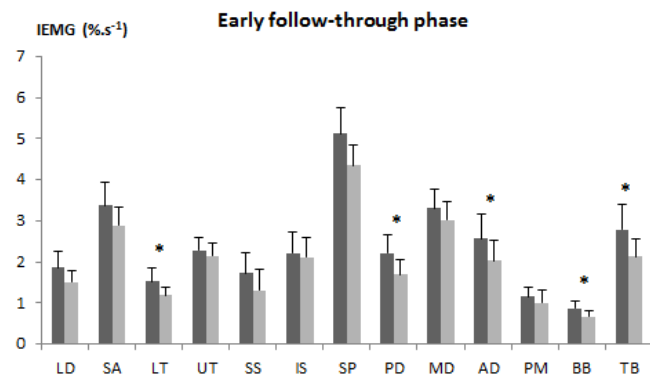
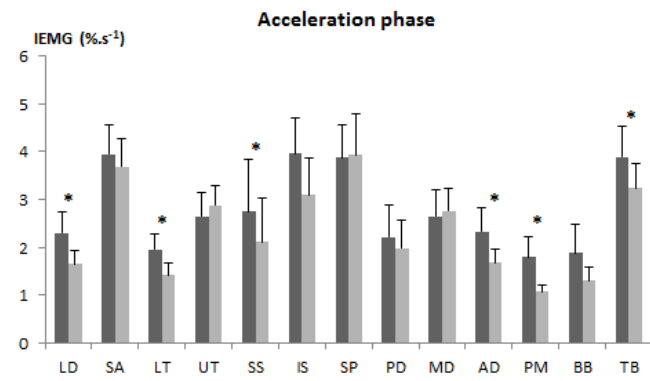
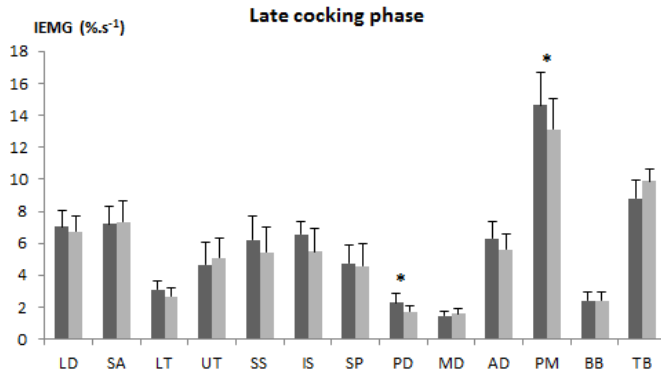
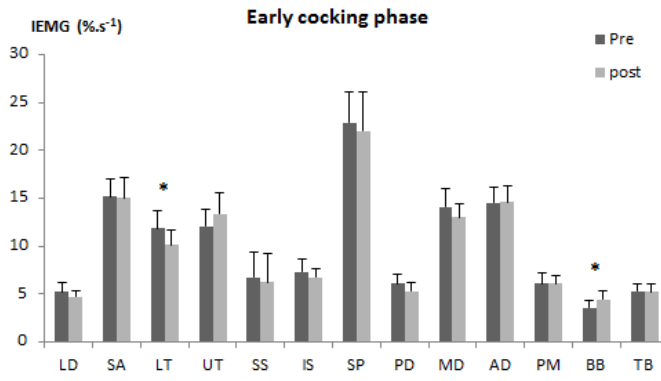
524 Figure 2: Humerothoracic (HT) and scapulothoracic (ST) joints before (in white) and after (in
 525 black) selective fatigue of the lower trapezius at the six serve events, with * for a significant
 526 difference at $p < 0.05$



527

528

529 Figure 3 Mean \pm standard error of the normalized integrated electromyography signal (in %) of
530 the latissimus dorsi (LD), serratus anterior (SA), lower trapezius (LT), upper trapezius (UT),
531 subscapularis (SS), infraspinatus (IP), supraspinatus (SP), posterior deltoid (PD), middle
532 deltoid (MD), anterior deltoid (AD), major pectoralis (PM), biceps (BB), and triceps (TB)
533 during the early (duration: 0.65 ± 0.03 s) and late cocking (0.22 ± 0.01 s), acceleration ($0.09 \pm$
534 0.01 s) and early follow-through (0.08 ± 0.01 s) phases of the tennis serve before (dark grey)
535 and after (light grey) LT selective fatigue, with * for significant difference before and after
536 fatigue at $p < 0.05$



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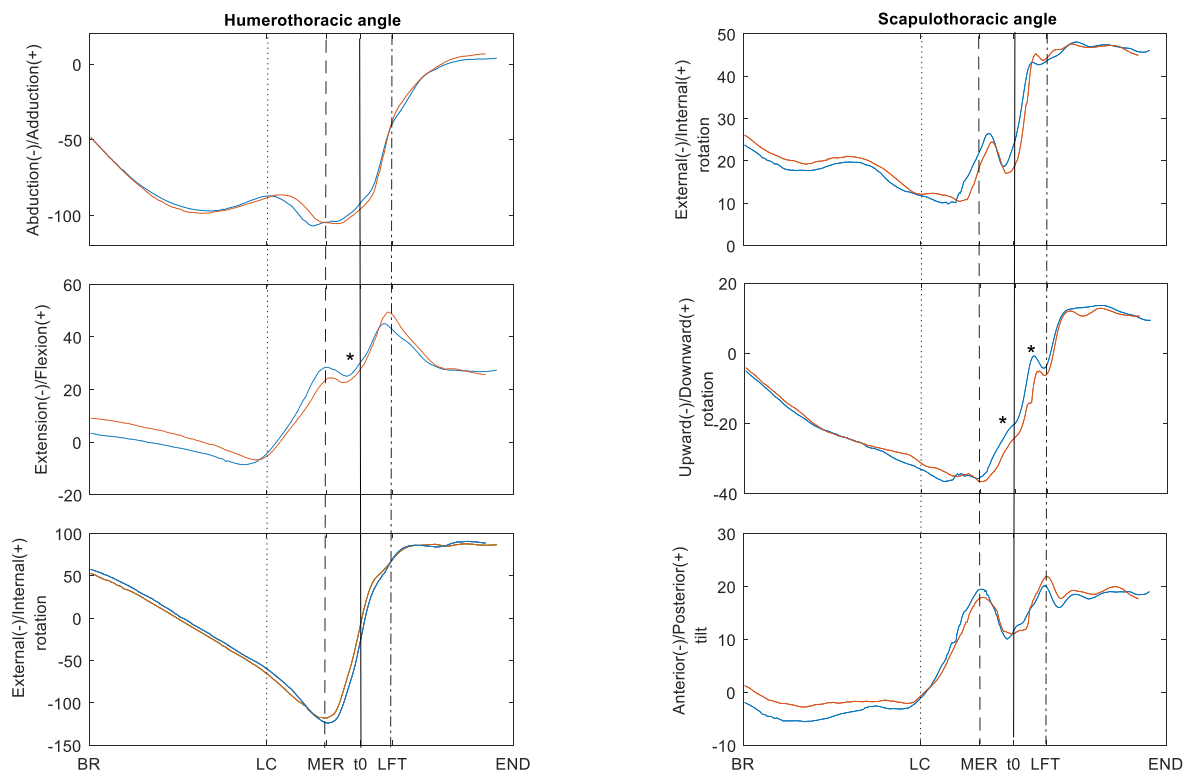
538

539 **List of Supplemental Digital Content**

540 **Supplemental Digital Content 1 (.docx):** Humerothoracic and Scapulothoracic joint

541 kinematics in degrees during the tennis serve before (blue) and after (red) selective fatigue of

542 the lower trapezius for a representative player.



543

544

545

546 **Supplemental Digital Content 2 (.docx):** Mean \pm standard error of the orientations (in
 547 degrees) of the humerothoracic (HT) and scapulothoracic (ST) joints before (pre) and after
 548 (post) selective fatigue of the lower trapezius at the six serve events, with bold for a
 549 significant difference at $p < 0.05$

HT			Abduction(-) adduction(+)	Flexion(+) extension(-)	Internal(+) external(-) rotation
Beginning of motion	Pre		-50.1 \pm 4.6	14.6 \pm 5.7	25.9 \pm 6.9
	Post		-48.1 \pm 4.8	15.2 \pm 4.9	27.6 \pm 8.5
	<i>p</i>		0.19	0.35	0.26
Beginning of Late cocking	Pre		-77.3 \pm 4.7	0.5 \pm 4.6	-64.1 \pm 4.9
	Post		-76.4 \pm 4.8	2.6 \pm 4.3	-66.8 \pm 6.0
	<i>p</i>		0.28	0.12	0.18
MER ¹	Pre		-97.5 \pm 5.1	36.1 \pm 4.8	-125.5 \pm 6.8
	Post		-98.0 \pm 5.1	39.3 \pm 4.7	-123.9 \pm 6.8
	<i>p</i>		0.39	0.08	0.24
Impact	Pre		-93.1 \pm 6.3	39.9 \pm 5.1	-72.5 \pm 10.9
	Post		-94.4 \pm 6.8	43.6 \pm 5.0	-67.6 \pm 12.6
	<i>p</i>		0.38	0.02	0.17
End of Early follow-through	Pre		-74.4 \pm 11.1	50.8 \pm 2.9	18.2 \pm 12.9
	Post		-76.2 \pm 9.9	53.6 \pm 3.8	16.9 \pm 10.8
	<i>p</i>		0.34	0.12	0.44
End of motion	Pre		17.1 \pm 3.8	34.3 \pm 4.7	105.1 \pm 10.2
	Post		15.9 \pm 4.5	35.1 \pm 5.7	99.9 \pm 9.6
	<i>p</i>		0.30	0.36	0.01
ST			Internal(+) external(-) rotation	Upward(-) downward(+) rotation	Anterior(-) posterior(+) tilt
Beginning of motion	Pre		28.8 \pm 3.1	-8.9 \pm 3.1	-10.8 \pm 2.3
	Post		29.3 \pm 2.7	-9.0 \pm 3.2	-10.4 \pm 2.4
	<i>p</i>		0.17	0.22	0.16
Beginning of Late cocking	Pre		21.1 \pm 2.9	-27.2 \pm 3.5	-10.8 \pm 2.3
	Post		20.6 \pm 2.5	-26.3 \pm 4.1	-10.4 \pm 2.4
	<i>p</i>		0.24	0.22	0.35
MER ¹	Pre		26.9 \pm 2.9	-31.1 \pm 3.4	3.9 \pm 2.9
	Post		28.3 \pm 2.7	-32.2 \pm 2.7	4.4 \pm 3.1
	<i>p</i>		0.19	0.22	0.33
Impact	Pre		33.1 \pm 2.6	-28.9 \pm 3.3	5.6 \pm 2.5
	Post		33.3 \pm 3.0	-29.2 \pm 3.0	5.8 \pm 2.7
	<i>p</i>		0.45	0.35	0.47
End of Early follow-through	Pre		37.9 \pm 2.9	-21.8 \pm 3.6	6.2 \pm 3.9
	Post		39.1 \pm 2.6	-23.8 \pm 3.5	6.8 \pm 3.5
	<i>p</i>		0.26	0.10	0.32
End of motion	Pre		40.9 \pm 3.5	-3.4 \pm 3.2	8.2 \pm 4.1
	Post		41.6 \pm 3.3	0.2 \pm 3.2	6.2 \pm 4.6
	<i>p</i>		0.33	0.01	0.17

550 Note: ¹MER for humeral Maximum External Rotation

551 **Supplemental Digital Content 3 (.docx):** Envelopes of the electromyography signal
 552 normalized by maximum activation recorded during isometric maximum voluntary contractions
 553 (IMVC) for the anterior, middle, posterior deltoid, biceps, triceps, upper trapezius, pectoralis,
 554 infraspinatus, supraspinatus, subscapularis, latissimus dorsi, lower trapezius and serratus
 555 anterior muscles during the tennis serve, before (blue) and after (red) selective fatigue of the
 556 lower trapezius, for a representative player. The follow-through phase was colored in grey
 557 because the kinematics and the EMG signals were not analyzed during this phase. Note: BR
 558 stands for ball release, LC: beginning of the late cocking phase, MER: humeral maximum
 559 external rotation, t0: impact, LFT: beginning of the late follow-through phase

