Advances in Skeletal Muscle Function Assessment

Official Journal of the International Society of Tensiomyography
EDITORIAL
Swarup Mukherjee

EFFECTS OF ACTIVE RECOVERY ON MUSCLE FUNCTION FOLLOWING HIGH-INTENSITY TRAINING SESSIONS IN ELITE OLYMPIC WEIGHTLIFTERS
Article type: Original research
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Article type: Original research
Peter Francis, William Mc Cormack, Mark Lyons, Philip Jakeman
EDITORIAL

We are finally ‘over the bar’. I am absolutely delighted to announce the first issue of the journal – Advances in Skeletal Muscle Function Assessment (ASMFA).

It has been about a year since the first brick was laid in Vienna with the members of the International Society of Tensiomyography (ISOT) coming together to finalize the concept, structure, intent and direction for the journal. Starting from the scratch, and with minimal resources, we have travelled through challenges, both foreseen and unforeseen, navigated through rough patches with poise and composure to arrive at the point of triumph. The support from the ISOT members and the back-end guys has been instrumental in the process.

Skeletal muscle is one of the most dynamic and plastic tissue of the human body and contributes significantly to multiple functional outcomes. From a mechanical perspective, the primary role of skeletal muscles is to provide mechanical energy to generate force, power, and produce movement during sports and exercise as well in day-to-day living for functional independence. The dynamic nature of skeletal muscle is reflected by its specific adaptations to various forms of stimuli. The intrinsic properties of skeletal muscle have the capability to change throughout our life span. Factors like growth, maturation, ageing, disease, exercise training, injury, fatigue, occupation, lifestyle can lead to change in the work capacity that can be measured as alterations in the different muscle function parameters. Therefore, the measurement of skeletal muscle function parameters has the potential for application to diverse fields like sports and exercise training and performance, injury recovery and rehabilitation, occupational medicine and work ergonomics, clinical and physiological research and the ageing population.

Modern technology has led to the emergence of highly sensitive, light-weight, portable, non-invasive and relatively inexpensive sensors capable of advanced signal analysis and measurement of muscular activities related to underlying neuromuscular parameters thus allowing reliable assessment of skeletal muscle functions. In the recent years, there has been a surge in research especially related to the application of non-invasive methods like surface electromyography, sonomyography, mechanomyography and tensiomyography for the measurement of various muscle functions. Moreover, owing to continued technological advancements, sophisticated newer generation prototypes for measuring muscle function, biosensors and wearable technologies are being developed all over the world. The ASMFA journal provides the perfect platform for sharing the research developments on various technologies to measure different functional characteristics of skeletal muscle and its application in diverse fields.

This issue includes articles with different flavours. The team from Germany provides rich evidence on the effects of repeated active versus passive recovery on muscle function in elite Olympic weightlifters. The second article is a technical report from the Leeds Beckett University researchers providing the guidelines to assess lower limb muscle contractile properties in football players using Tensiomyography. The third article from the team of Spanish researchers is on the modern sport of futsal. They provide practically purposeful evidence on the measurement of lateral symmetry and muscle response speed during in-season in elite futsal athletes. The fourth article by the researchers in Leeds and Ireland investigates the rate of torque development in lower limb muscles and its association with functional tasks and response to an intervention in healthy elderly females.

Hope you enjoy the issue and find it purposeful in your work.

Dr Swarup Mukherjee, MD, PhD
Editor-in-Chief
ABSTRACT

This study investigated whether the repeated use of an active recovery (ACT) program is beneficial for promoting recovery of muscle function during an intensive training phase in elite Olympic weightlifters. Using a crossover design, eight competitive weightlifters (7 male; 1 female) from the German national Olympic team participated in a two-day microcycle, comprising of four high-intensity training sessions, with either ACT or passive recovery (PAS) following the session. Barbell velocity during the clean pull, countermovement jump (CMJ) height, muscle contractile properties using tensiomyography (TMG), creatine kinase activity (CK), muscle soreness (DOMS) and perceived overall recovery and stress were measured. After termination of the microcycle, the sport-specific performance during all clean pull intensities (85% 1RM, ACT: Effect size (ES) = -0.20, PAS: ES = -0.50; 90% 1RM, ACT: ES = -0.29, PAS: ES = -0.35; 95% 1RM, ACT: ES = -0.41, PAS: ES = -0.20; P > 0.05) decreased. Both CK (ACT: ES = 2.11, PAS: ES = 1.41; P = 0.001) and DOMS (ACT: ES = 1.65, PAS: ES = 2.33; P = 0.052) considerably increased. Similarly, ratings of perceived recovery and stress were adversely affected in ACT and PAS, whereas changes in CMJ height and TMG muscle contractile properties remained trivial in both conditions. No practically meaningful differences in changes of the outcome measures were found between ACT and PAS, however there were variable individual responses to ACT. In conclusion, the short-term implementation of an individualized ACT program does not seem to enhance recovery from training-induced fatigue more effectively than PAS. However, because of the inter-individual variability in responses to ACT, it may be beneficial at the individual level.

KEY WORDS:
Fatigue; Performance; Strength training; Muscle damage; Power athletes

EFFECTS OF ACTIVE RECOVERY ON MUSCLE FUNCTION FOLLOWING HIGH-INTENSITY TRAINING SESSIONS IN ELITE OLYMPIC WEIGHTLIFTERS

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INTRODUCTION

Weightlifting is a dynamic strength and power sport comprising two competitive lifts, the snatch and the clean and jerk, which require the athlete to develop very high peak forces and contractile rates of force development [1]. Therefore, the training plan of competitive weightlifters includes multiple daily high-intensity training sessions, 5-7 days per week, of the same major muscle groups and similar multi-joint movement exercises as in the competitive lifts [1-3]. Such frequent exposure to strenuous high-resistance training loads in close density places high demands on their recovery abilities in terms of a rapid performance restoration after intense training sessions [4, 5]. Insufficient recovery may adversely affect the capability to cope with the demands of the training volume and intensity during the subsequent training sessions [5]. Therefore, optimizing post-training recovery during intense training periods may effectively reduce the fatigue incurred from training or decrease the severity of fatigue symptoms [6]. This may also allow the athlete to tolerate higher training loads with respect to frequency, volume and intensity and to increase the impact of a given training stimulus [5].

Active recovery (ACT) is a commonly used method by athletes immediately after training or competition to promote the recovery mechanisms at the muscular and psychological level, and thus restore performance more quickly [7, 8]. ACT strategies usually include low-to-moderate intensity aerobic-type dynamic activities (i.e., swimming, cycling, running) at 30-60% of the individual aerobic capacity or 60-100% of the individual lactate threshold for a minimum duration of 10 to 30 minutes [7, 8]. ACT from intense muscular strain increases muscle perfusion, promotes nutrient transport to damaged tissues, enhances clearance of waste products and elimination of muscle cell debris without causing more muscle damage, as well has a temporary analgesic effect on sore muscles [7, 9, 10]. In addition, post-resistance exercise ACT strategy does not inhibit the acute anabolic response or suppress ribosome biogenesis and subsequent muscle protein synthesis, and also does not affect long-term adaptations in strength and muscle mass [11, 12]. While ACT immediately after a match in rugby players has been reported [13] to significantly speed-up muscle damage recovery (measured by creatine kinase activity) compared to passive recovery (PAS), Suzuki et al. revealed no beneficial effect of post-match ACT on reducing muscle damage in collegiate rugby players, although the athletes seemed to benefit from an increased psychological recovery [14]. Furthermore, while ACT improve recovery of isometric leg extensor strength in untrained women 72 hours after an eccentric exercise protocol promoting muscle damage [9], other studies reported no useful effects of post-competition ACT on the rate and magnitude of alterations in neuromuscular performance as well as on biochemical and perceptual changes in elite female soccer players [15], male futsal players [16] and male football players [17]. Therefore, the current evidence is conflicting, with a lack of studies on elite strength-power athletes investigating ACT as potentially effective recovery method. Moreover, previous studies have primarily examined effects of ACT on recovery after a single training session. The effect of repeated use of ACT during intense training periods is yet to be investigated. Therefore, the present study aimed to investigate the short-term effectiveness of repeated ACT compared with PAS during a 2-day high-intensity training microcycle on sport-specific performance as well as on neuromuscular, biochemical and perceptual markers of fatigue in elite Olympic weightlifters.

We hypothesized, first, that the training program would induce an acute decrease in physical performance as well as adverse effects in several markers of fatigue. Our second hypothesis was that the application of ACT would accelerate recovery more effectively than PAS during the training period and thus would decrease the magnitude of training-induced fatigue.

METHODS

Experimental design

A cross-over study design was used to investigate the effects of repeated ACT compared to PAS on the recovery pattern of sport-specific performance and several markers of fatigue (Figure 1). Participants completed two similar training microcycles separated by a two-week wash-out period in order to control training progress. The two training periods were embedded inside consecutive “heavy load weeks” to ensure the induction of fatigue. Inside the first microcycle (MC 1), the participants were allocated to either an ACT or PAS intervention, matched on competition performance. In the second microcycle (MC 2), the participants changed the recovery modalities.

Sport-specific performance comprising maximal barbell velocity during the clean pull (CP), as well as markers of fatigue including countermovement jump (CMJ) performance, TMG muscle contractile properties (maximal muscle belly displacement, Dm; muscle contraction velocity, V90), muscle damage (serum creatine kinase activity, CK), muscle soreness (Delayed Onset Muscle Soreness, DOMS), and perceived stress and recovery levels (using the novel Short Recovery and Stress Scale, SRSS [25]) were collected one day before (Pre) and one day after (Post) completing the microcycles. These consisted of four training sessions, morning (9.30 – 11 am) and afternoon (3.30 – 5 pm), organized over two training days (Figure 1). Immediately after each training session, the participants performed either ACT (submaximal rowing ergometer exercise) or PAS (resting in a seated position) for 15 minutes. In addition, CMJ and SRSS were also measured before (pre T2, pre T3, and pre T4) and after the training sessions (post T1, post T2, post T3, and post T4) as well as after ACT or PAS (post R1, post R2, post R3 and post R4).

Figure 1. Schematic representation of the study design. SRSS: Short Recovery and Stress Scale; DOMS: Delayed Onset Muscle Soreness; CK: serum Creatine Kinase; TMG: Tensiomyography; CMJ: Countermovement Jump, CP: Clean Pull; ACT: Active recovery; PAS: Passive recovery; T: Training session, R: Recovery intervention.
MEASUREMENTS

Sport-specific performance: The CPs were performed in a fixed order at Pre and Post, and were used to measure maximal barbell velocity corresponding to 85% (CP85), 90% (CP90) and 95% (CP95) of the maximum load (i.e., 1RM). During CPs, participants vertically lifted the barbell (using a shoulder-width grip) in one continuous movement with the goal to maximize barbell velocity [1]. The barbell was aggressively accelerated by explosively extending the body upward using lower-body triple extension (fully extended hips, legs and ankles) [18]. Following the completion of the CP, the barbell was dropped to the floor.

Maximal barbell velocity is an important indicator of sport-specific performance [19] and was determined through a special measuring system based on video image analysis using a camcorder (Panasonic GS 500, Panasonic Corporation, Kadoma, Japan) and analogous software package (Realanalyzer, IAT Leipzig, Germany) with the participants standing on a measuring platform. During each attempt, the center of the outer weight plate was set as a point of reference and then digitally tracked by a video camera using a sampling rate of 50 Hz. Thus, the vertical displacement of the barbell could be measured as a function of time and, consequently, the maximal barbell velocity besides a variety of other kinematic variables. Adequately high reliability scores for overall CP [cm·s⁻¹] were previously found among elite weightlifters, n = 20. Intra-class correlation coefficient (ICC) = 0.717, typical error (TE) = 6.4, coefficient of variation (CV) = 3.4%.

Jump performance: CMJs were performed at Pre and Post and additionally before and after each training session as well as after ACT or PAS using a contact platform (Haynl Elektronik, Schönebeck, Germany). During the CMJ, the participants placed the hands on the hips and squatted down to a self-selected level before jumping for maximal height. Jump height was calculated from the flight time. At each measurement point, the participants performed three CMJs and the mean jump height was taken for later analysis. Reliability scores were previously calculated in our own laboratory and considered highly reliable in CMJ [cm] n = 38: ICC = 0.915, TE = 1.86, CV = 3.7%.

Muscle contractile properties: The TMG was used as a non-invasive and involuntary (independent of central activation) method to determine muscle contractile properties of the lower extremity without inducing additional fatigue [20]. TMG measurements were conducted at Pre and Post using an electrical stimulator (TMG-S2), analogous TMG-OE 3.0 software, as well as a spring-loaded displacement sensor tip (TMG-BMC, Ljubljana, Slovenia) with a prefixed tension of 0.17 N m⁻¹ positioned on the centre point of the belly of the vastus medialis muscle [20]. The sensor location was carefully determined before the first TMG measurement for each individual participant. The muscular geography of the vastus medialis is generally well displayed, especially in weightlifters. While the participants were asked to perform a voluntary knee extension, the centre point of the muscle belly could thus be estimated relatively accurately, taking into account the specific fiber orientation (i.e., vastus medialis muscle fibres run at ~55° angle medial to the tendon of quadriceps muscle). This position was considered to be the point of maximal muscle belly displacement. The measuring point was then marked with a dermatological pen and was kept constant during the study period. The self-adhesive electrodes were placed symmetrically approximately 5 cm away from the sensor. TMG measurements were performed in a supine position and a knee joint angle of 120° was held constant using supporting pads. The TMG muscle contractile properties assessed were Dm (indicator of muscle stiffness or muscle contractile force), and the mean velocity of muscle contraction from the onset of electrical stimulation until 90% of Dm (V90) [20, 21].

During squat exercise, an integral component in weightlifting training routines, the activity of vastus medialis and laterals is greater than of rectus femoris. The vasti muscles equally contribute to muscle force output, and they produce approximately 50% greater muscle force output as the rectus femoris [22]. Therefore, the muscle contractile properties of vastus medialis were measured in this study, since we expected a greater responsiveness due to higher mechanical strains. Reliability scores were previously determined in our own laboratory and considered sufficient reliable in Dm [mm], n = 20: ICC = 0.918, TE = 1.0, CV = 9.3% and in V90 [mm·s⁻¹], n = 20: ICC = 0.781, TE = 16, CV = 9.9%.

Muscle damage: Venous blood samples for analysis of serum creatine kinase (CK) activity were used as indirect evidence of muscle damage and taken at Pre and Post (between 8 and 10 am). The blood samples were collected using 7.5 mL serum gel tubes with clotting activator (Sarstedt; Nümbrecht, Germany). The samples were positioned upright for 20 minutes and subsequently centrifuged at 3500 rpm for 15 minutes. Serum was aliquoted into microtubes (Sarstedt; Nümbrecht, Germany), frozen at -80°C within 60 minutes after collection, and stored for later analysis. The determination of CK activity was then conducted by routine techniques (UniCell DxC 600 Synchron; Beckmann Coulter GmbH, Krefeld, Germany). Reliability scores were calculated with the present participants and considered sufficient reliable in CK [U·L⁻¹]: ICC = 0.825, TE = 94, CV = 17.7%.

Muscle soreness: DOMS was measured at Pre and Post using a visual analogue scale (VAS). The VAS consists of a 10 cm line with endpoints labeled as “no pain” (left) and “unbearable pain” (right). The participants palpated their lower limbs and made a vertical mark at a point on the line that best represented their current rating of soreness. The score was the distance in cm from the left side of the scale to the point marked [23]. A 5-10mm change in pain rating on a 100mm VAS has been considered a small effect of clinical importance [24]. To be more conservative we decided to define the 2-fold of the lower limit value as the smallest worthwhile change (SWC, 10mm) in the present study.

Perceived recovery and stress: The subjective rating of perceived recovery and stress was determined at Pre and Post, before and after the training sessions and recovery interventions as well as before bedtime (pre-sleep) using the SRSS [25]. The participants provided responses to eight items on a rating scale ranging from “0” (does not apply at all) to “6” (fully applies). Numbers “1” to “5” were undefined and used to delineate the degrees of perceived recovery and stress between the two endpoints of the scale. The items used in this study were “Physical Performance Capability” (PPC), “Overall Recovery” (OR), “Muscular Strain” (MS), and “Overall Stress” (OS). Scores for internal consistencies of the SRSS were previously examined among elite
athletes and considered to be sufficient (n = 574; Cronbach’s α > 0.72) [25]. Jaeschke and co-workers [26] reported a minimum clinical important difference of 0.5 per item on a 7-point Likert scale. As already emphasized, to be more conservative we defined the 2-fold of this value as the SWC (change of 1.0 per item) in the present study.

Recovery intervention: ACT was started within 5 min after each training session with 15 min supervised rowing ergometer (Concept2, Hamburg, Germany) exercise at a submaximal load corresponding to approximately 1 Watt per kg body weight and with a stroke frequency of < 20 per minute. A specific pilot study, previously conducted, confirmed this selected intensity as almost completely aerobic-type exercise with blood lactate values < 2 mmol/l and RPE values ranging between 2 and 3 (easy to moderate) on a CR-10 scale.

Training program: The participants completed a total of 4 training sessions (2 sessions / day) during the two microcycles (Figure 1), each with similar training content and volume. The total training load as well as the mean barbell load is given in Figure 2. Besides the two competitive exercises including the snatch and the clean and jerk and their various derivatives, the participants basically performed high-load back and front squats, clean and snatch pulls as well as overhead and push press exercises.

Figure 2. Total training load and mean barbell load in MC 1 and MC 2 as well as in ACT and PAS interventions during the examination period. MC, Microcycle; ACT, Active recovery; PAS, Passive recovery; T, trivial change in mean.

PARTICIPANTS

Eight competitive male (n = 7) and female (n = 1) elite weightlifters from the German national Olympic team participated in the study (Table 1). They were informed about the experimental procedures and they provided written consent for participation. The study was approved by the local Ethics Committee of the Medical Faculty of the Ruhr-University Bochum and was performed according to the guidelines of the Declaration of Helsinki.

Table 1. Anthropometric and performance-related characteristics of the participants

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Weight class (kg)</th>
<th>Age (yrs)</th>
<th>Body weight (kg)</th>
<th>Body height (cm)</th>
<th>Snatch (kg)</th>
<th>Clean &amp; Jerk (kg)</th>
<th>Duel (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>male</td>
<td>77</td>
<td>23</td>
<td>78</td>
<td>165</td>
<td>150</td>
<td>190</td>
<td>340</td>
</tr>
<tr>
<td>#2</td>
<td>male</td>
<td>94</td>
<td>29</td>
<td>88</td>
<td>171</td>
<td>156</td>
<td>205</td>
<td>359</td>
</tr>
<tr>
<td>#3</td>
<td>male</td>
<td>105</td>
<td>29</td>
<td>105</td>
<td>176</td>
<td>167</td>
<td>205</td>
<td>370</td>
</tr>
<tr>
<td>#4</td>
<td>male</td>
<td>77</td>
<td>32</td>
<td>81</td>
<td>172</td>
<td>151</td>
<td>183</td>
<td>332</td>
</tr>
<tr>
<td>#5</td>
<td>male</td>
<td>85</td>
<td>22</td>
<td>87</td>
<td>167</td>
<td>145</td>
<td>185</td>
<td>330</td>
</tr>
<tr>
<td>#6</td>
<td>male</td>
<td>105</td>
<td>26</td>
<td>132</td>
<td>191</td>
<td>185</td>
<td>215</td>
<td>400</td>
</tr>
<tr>
<td>#7</td>
<td>male</td>
<td>105</td>
<td>32</td>
<td>106</td>
<td>175</td>
<td>178</td>
<td>218</td>
<td>391</td>
</tr>
<tr>
<td>#8</td>
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<td>75</td>
<td>19</td>
<td>74</td>
<td>172</td>
<td>92</td>
<td>112</td>
<td>204</td>
</tr>
</tbody>
</table>

Mean ± SD: 26.5±4.8, 93.9±19.3, 173.6±7.9, 153.0±28.4, 189.1±33.8, 340.8±61.1.

Statistical analyses were performed with the IBM SPSS statistical package (version 22; IBM, Chicago, IL, USA). Data are presented as mean ± SD, unless otherwise stated. Assumption of normality was confirmed by means of Shapiro-Wilk's test before conducting any parametric tests. A repeated-measures analysis of variance (ANOVA) with factors recovery type and time was calculated to determine differences in all analyzed variables between ACT and PAS as well as between the Pre and Post measurement points. Violation of sphericity was adjusted by Greenhouse-Geisser correction. Bonferroni post-hoc comparisons were used if ANOVA main effect was significant. The p < 0.05 criterion was used to constitute statistical significance.

In addition, the data were evaluated through analyses of practical relevance using magnitude-based-inferences (MBI), calculated from 90% confidence limits using published spreadsheets (available at www.sportsci.org), in order to assess the probability that the magnitude of differences in the changes between ACT and PAS are practically meaningful [27]. The smallest worthwhile change (SWC) was defined as 0.5 of the typical proportion in performance (CP and CMJ) as well as in markers of muscle contractile properties (Dm and V90) and muscle damage (CK) [27, 28]. In DOMS, the SWC was set as a 10mm change on the VAS [24], whereas in SRSS the SWC was defined as a minimum change of 1.0 per item [26]. The between-condition differences in changes of all analyzed parameters were calculated from adjusted pre-values and allocated a qualitative descriptor representing the probability that the true value is of the observed magnitude [28]. Qualitative inferences were considered as chances (%) of having a negative (-), trivial, or positive (+) effect, and evaluated as follows: < 0.5%, almost certainly not; 0.5 - 5.0%, very unlikely; > 5.0% - 25.0%, unlikely; > 25.0% - 75.0%, possibly; > 75.0% - 95.0%, likely; > 95.0% - 99.5%, very likely; > 99.5%, most likely [27]. If the chance of having a substantially positive or negative effect was both > 5%, the true change was assessed as ‘unclear’. Standardized changes...
between measurement points and standardized differences in changes between ACT and PAS were also calculated using the effect size (ES), and threshold values of 0.0 – 0.19, 0.20 – 0.59, 0.60 – 1.19, 1.20 – 1.99, and > 2.00 were considered trivial, small, moderate, large, and very large, respectively [27, 28].

RESULTS

There was a significant main effect for time in CK activity and perceived MS (Table 2), while the other variables remained statistically unaffected (Table 2 and 3). Considering the ES statistic, the training microcycle induced large to very large effects in markers of perceived recovery and stress, showing a decrease in PPC (ACT: ES = -0.20, PAS: ES = -0.50; CP90, ACT: ES = -0.29, PAS: ES = -0.35; CP95, ACT: ES = -0.41, PAS: ES = -0.20) as well as trivial Pre-Post changes in markers of jump performance (CMJ, ACT: ES = 0.06, PAS: ES = 0.15) and muscle contractile properties (Dm, ACT: ES = 0.14, PAS: ES = 0.09; V90, ACT: ES = 0.10, PAS: ES = -0.20) in both recovery conditions (Table 3). Moreover, there was no significant recovery type × time interaction between Pre and Post in all the analyzed variables. In addition, magnitude-based inferences revealed no beneficial or detrimental effects of ACT reflected by no meaningful differences in Pre-Post changes between ACT and PAS, both in sport-specific performance and in markers of fatigue (Tables 2 and 3).

A more detailed presentation of neuromuscular performance (CMJ) and selected markers of perceived recovery and stress (PPC and MS) before and after the training and recovery sessions during the entire training period are shown in Figs 3-5. Overall, the total mean change from baseline in CMJ was -1.9 ± 5.1 % in ACT and 1.8 ± 4.2 % in PAS; however, the difference in total changes between ACT and PAS was not significant and was deemed practically “unclear”. More precisely, ACT induced a likely decreased jump performance immediately post R2 and post R3, while this was not apparent following PAS. Our data further showed that CMJ height very likely differed between the two recovery conditions at post R2 in favor of PAS. These findings are also supported by the observed changes in markers of perceived recovery (PPC) and

### Table 2. Markers of muscle damage and muscle soreness as well as perceived recovery and stress at Pre and Post, the absolute mean changes between Pre and Post, and the differences in the absolute mean changes between the recovery modes.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mode</th>
<th>Pre</th>
<th>Post</th>
<th>Time</th>
<th>∆Post - Pre</th>
<th>Group × Time Interaction</th>
<th>∆ACT – PAS</th>
<th>Qualitative inference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Muscle damage &amp; muscle soreness</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CK [U · L-1]</td>
<td>ACT</td>
<td>254 ± 106</td>
<td>558 ± 215</td>
<td>0.001</td>
<td>300 ± 149</td>
<td>0.816</td>
<td>-25 ± 166</td>
<td>Unclear</td>
</tr>
<tr>
<td>PAS</td>
<td>241 ± 91</td>
<td>562 ± 234</td>
<td></td>
<td>324 ± 203</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOMS [mm]</td>
<td>ACT</td>
<td>10 ± 9</td>
<td>23 ± 18</td>
<td>0.052</td>
<td>13 ± 13</td>
<td>0.536</td>
<td>-5 ± 17</td>
<td>Unclear</td>
</tr>
<tr>
<td>PAS</td>
<td>11 ± 7</td>
<td>29 ± 28</td>
<td></td>
<td>19 ± 30</td>
<td></td>
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<tr>
<td><strong>Perceived recovery and stress</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPC [0-6]</td>
<td>ACT</td>
<td>4.8 ± 0.9</td>
<td>4.1 ± 1.1</td>
<td>0.225</td>
<td>-0.6 ± 1.0</td>
<td>0.999</td>
<td>0.5 ± 0.7</td>
<td>Likely trivial</td>
</tr>
<tr>
<td>PAS</td>
<td>4.3 ± 0.7</td>
<td>3.6 ± 1.5</td>
<td></td>
<td>-1.0 ± 1.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OR [0-6]</td>
<td>ACT</td>
<td>4.6 ± 0.6</td>
<td>3.5 ± 0.8</td>
<td>0.069</td>
<td>-1.0 ± 0.7</td>
<td>0.492</td>
<td>0.0 ± 0.6</td>
<td>Very likely trivial</td>
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<tr>
<td>PAS</td>
<td>4.3 ± 0.8</td>
<td>3.5 ± 1.4</td>
<td></td>
<td>-1.0 ± 1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MS [0-6]</td>
<td>ACT</td>
<td>1.4 ± 1.2</td>
<td>2.9 ± 1.0</td>
<td>0.015</td>
<td>1.4 ± 1.0</td>
<td>0.434</td>
<td>0.4 ± 1.1</td>
<td>Likely trivial</td>
</tr>
<tr>
<td>PAS</td>
<td>1.6 ± 0.9</td>
<td>2.5 ± 1.3</td>
<td></td>
<td>1.0 ± 1.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OS [0-6]</td>
<td>ACT</td>
<td>0.9 ± 0.6</td>
<td>2.3 ± 1.2</td>
<td>0.084</td>
<td>1.4 ± 1.0</td>
<td>0.379</td>
<td>0.4 ± 1.1</td>
<td>Likely trivial</td>
</tr>
<tr>
<td>PAS</td>
<td>1.4 ± 1.2</td>
<td>2.1 ± 1.7</td>
<td></td>
<td>1.1 ± 1.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ACT, Active recovery; PAS, Passive recovery; CK, serum Creatine Kinase; DOMS, Delayed Onset Muscle Soreness; PPC, Physical Performance Capability; OR, Overall Recovery; MS, Muscular Strain; OS, Overall Stress.

*calculated from adjusted pre-values; †significantly different from Pre; A Indicates small effect size (ES = 0.20 - 0.59); B Indicates moderate effect size (ES = 0.60 - 1.19); C Indicates large effect size (ES = 1.20 - 1.99); D Indicates very large effect size (ES > 2.00); T Indicates trivial effect size (0.00 – 0.19).
stress (MS), showing a possibly to very likely more decreased PPC and a possibly to very likely more increased MS after almost each ACT intervention compared with PAS. Interestingly, prior to the afternoon training session (pre T2 and pre T4), jump performance was likely to very likely increased in the PAS condition. This however was only evident pre T4 in ACT, while changes in CMJ height pre T2 were very likely lower in ACT compared to PAS. Individual Pre-Post changes in markers of sport-specific performance (CP85, CP90, and CP95) of some athletes are shown in Fig. 6. Subject #1 showed a likely improved performance in CP85 and CP90 following ACT, while performance in CP90 was likely decreased following PAS. This was accompanied by higher ratings of perceived recovery (PPC and OR) in ACT compared with PAS. In contrast, subject #8 showed a likely decreased performance in CP95 and CP90 after the ACT intervention, while changes in overall performance remained trivial in the PAS intervention. This came also along with increased

![Figure 3](image1.png)

**Figure 3.** Differences in percentage changes from Pre between ACT and PAS in Countermovement Jump (CMJ) performance during the entire training period. Data are mean ± SD. SWC, Smallest Worthwhile Change (SWC = 0.5 x CV); ACT, Active recovery; PAS, Passive recovery; T, Training session; R, Recovery intervention; circles in dashed and solid lines represent likely and very likely changes from Pre; * indicates very likely between-ACT-PAS difference.

![Figure 4](image2.png)

**Figure 4.** Differences in changes from Pre between ACT and PAS in perceived PPC (Physical Performance Capability) during the entire training period. Data are mean ± SD. SWC, Smallest Worthwhile Change (SWC = 1 point score); ACT, Active recovery; PAS, Passive recovery; T, Training session; R, Recovery intervention; circles in dashed and solid lines represent likely and very likely changes from Pre; * indicates possibly between-ACT-PAS difference; ** indicates likely between-ACT-PAS difference.
and decreased ratings of perceived stress (MS and OS) in ACT and PAS, respectively. With regard to subject #3, overall performance was likely to most likely impaired following the PAS condition, whereas performance was only compromised to a lesser extent in CP85 following the ACT condition. In addition, this was supported by a greater increase in ratings of perceived stress in PAS compared to ACT. For the remaining participants, there were no beneficial or deleterious effects of ACT compared with PAS on markers of sport-specific performance.

**DISCUSSION**

This study investigated the short-term effectiveness of the repeated use of ACT on sport-specific performance as well as on neuromuscular, biochemical and perceptual measures in Olympic weightlifters during a 2-day high-intensity training microcycle. Contrary to our initial hypothesis, ACT had no significant beneficial or deleterious group effects compared to PAS on the recovery pattern of performance and selected markers of fatigue. This is similar to a study from our research group, showing similar impacts on performance as well as on markers of muscle damage and measures of subjective well-being following intense strength training sessions [4, 30].

The study found large to very large increases in CK and DOMS from Pre to Post-training both in the ACT and PAS condition (Table 2). These changes could be attributed to the mechanical disruption of muscle contractile components and the subsequent inflammatory response as a result of intense training load during the preceding days [31] suggesting that CK and DOMS were sensitive to detect training-induced fatigue. ACT strategies hastens recovery by increase in local blood flow which promotes nutrient transport to damaged tissues and enhances removal of waste products and muscle-cell debris, as well as by causing a transient analgesic effect on perceived muscle soreness [7, 9, 10]. However, our results did not support these recovery mechanisms since the repeated use of ACT was not more effective than PAS in enhancing the clearance rate of CK or alleviating the sensation of DOMS (Table 2).

While a previous study also reported no beneficial effects of post-competition ACT on changes in CK concentrations or ratings of muscle soreness in elite female soccer players [15] or male futsal and football players [16, 17], Gill et al [13] demonstrated that ACT immediately performed after a rugby match significantly decreased the CK activity after 36 hours and 84 hours in elite male players, as compared to PAS. However, in that study the CK activity was analyzed by transdermal exudate sampling, a measurement technique which has not yet been validated [7], making it difficult to compare the present CK values obtained from the blood serum with those reported by Gill et al [13]. Regarding the analgesic effect of ACT on muscle soreness, a study [10] showed that muscle soreness was alleviated immediately after light concentric exercise 1 to 4 days after strenuous eccentric exercise of the arm flexors. Similarly, Andersen et al [32] found that ACT provided acute relief of muscle soreness up to 60 minutes following mild elastic tubing 48 hours after maximal eccentric contractions for the upper trapezius. The underlying potential mechanisms of exercise-induced pain relief are believed to be associated with several central neural mechanisms [33]. In this context, the activation of the endogenous opioid system during exercise, causing an enhanced endorphin release by neurons in the central nervous system, may inhibit the transmission of pain, and thus increasing the pain threshold and pain tolerance [10, 33]. Furthermore, exercise-related increased input from group Ia, Ib and II muscle afferents could interfere with the pain sensations associated with group III and IV afferent activity, probably by interneurons that presynaptically inhibit nociceptive input from ascending pathways at the level of the nociceptive input from ascending pathways at the level of the nociceptive input from ascending pathways at the level of the nociceptive input from ascending pathways.
spinal cord [10, 33]. However, the analgesic effect of exercise is thought to be temporary and not long-lasting, since with the cessation of exercise, muscle soreness may gradually return during the post-exercise period [32, 33]. This could explain why in the current study the repeated use of ACT immediately performed after each training session was ineffective to reduce the sensation of DOMS in the days after its application. Previous research also reported no sustained effects of ACT on relieving muscle soreness [15-17]. Based on the conditions of this study, the present ACT strategy comprising 15 minutes of submaximal whole-body rowing exercise was not more beneficial than PAS. We therefore do not have a conclusive basis to recommend ACT for accelerating muscle tissue recovery or attenuating muscle soreness. However, it should be noted that ACT did not have detrimental effects on the two measures, CK and DOMS.

The 2-day training program also induced meaningful fatigue effects in perceptual markers of the SRSS, demonstrating a decrease in perceived recovery (i.e., PPC and OR) and an increase in perceived stress (i.e., MS and OS) in both recovery interventions. However, there were no differences in Pre-Post changes between ACT and PAS (Table 2) suggesting that the subjective markers were sensitive to changes in training-related fatigue, irrespective of recovery mode, and ACT may not be a more effective strategy to decrease the magnitude of fatigue or speed-up recovery at the perceptual level, as compared to PAS. Our observations are in line with those in the study of Tesserore and associates [16], reporting no beneficial effects of post-game ACT on the recovery-stress state of male futsal players. Conversely, a study by Suzuki et al. [14] showed that low-intensity ACT immediately after a rugby match favored a better psychological recovery. This contradictory finding may be related to the different rating scale used to assess the athlete’s psychological condition, making comparisons difficult. In this regard, Suzuki and colleagues [14] used the Profile of Mood States and showed a decreased tension score in the ACT group 48 hours post-competition. However, this was the only significant effect on participants’ mood states among six different subscales, and that observed within-group change was not significantly different from the control group. This raises concerns on the effectiveness of ACT on accelerating mental recovery. The present results indicate, however, that the repeated use of ACT during a short period of intense training does not adversely or favorably affect markers of perceived recovery and stress, allowing its application after careful consideration by coaches and practitioners.

Regarding measures of performance, the current study demonstrated that maximal barbell velocity in CP over all relative intensities (CP85, CP90, and CP95) slightly decreased from Pre to Post-training both in ACT and PAS (Table 2). It is assumed that the overall decline in CP performance could be related to the specific fatiguing load of the preceding high-intensity training sessions. This may hamper the production of very high peak forces and contractile rates of force development, probably resulting in less peak power outputs during the execution of the CPs. Conversely, CMJ did not reflect changes in training-induced fatigue, since jump performance remained unaffected after the training period in both recovery conditions (Table 3). In this regard, it has been speculated that athletes might be capable to generate ‘one-off’ effort close to their maximum during a single jump test, although being in a fatigued condition [16]. Additionally, Häkkinen et al [4] found no systematic changes in the basic level of neuromuscular performance (i.e., maximal isometric force and maximal electromyographic activity of leg extensor muscles) during an intensive 1-week strength training period in elite weightlifters. Our results showed that ACT had no beneficial or deleterious effects on all measures of performance, evidenced by no differences in Pre-Post changes between ACT and PAS (Table 3). Furthermore, ACT did not enhance the proposed recovery mechanisms, and thus did not promote post-training recovery suggesting limitations in the use of ACT in strength and power athletes. It is however possible that a 2-day training period may be too short to induce sufficient fatigue in the performance measures, which might adversely affect the possibly short-term recovery-promoting effect of an ACT strategy [16]. Furthermore, our findings are in agreement with previous studies which demonstrated that post-match ACT did not positively or adversely affect the recovery pattern of neuromuscular performance in female and male team sport players [15-17]. Consequently, we recommend that coaches and practitioners should exercise caution and a sense of subjective judgment in the use of ACT for promoting recovery.

The muscle contractile properties (Dm and V90) determined using TMG remained unaffected after the training program in both recovery interventions (Table 3) indicating that the present TMG measures were insufficient to detect training-induced fatigue. The unimpaired muscle contractile function was unexpected, since changes in CK concentrations and DOMS indicated the presence of muscle damage and soreness. Previous studies have shown that muscle contractility was substantially compromised after high-intensity strength exercise of the elbow flexors as a result of myofibrillar disruptions, followed by the local inflammatory response and impairments in excitation-contraction coupling [21, 34]. This however was not evident in the present study, and the findings may in part be explained by the current high inter-individual variability in participants’ change scores and the lower severity of exercise-induced muscle damage as well as the differences in methodological design. Our findings are consistent with the findings of Rey et al. [35] who showed that immediate post-training ACT did not positively or negatively affect muscle contractile properties 24 hours after training in male soccer players. Interestingly, the neuromuscular performance (i.e., CMJ) in our participants tended to be more impaired in the ACT than in the PAS condition (Figure 3) during the entire training period, reflected by a negative trend in the total mean change of CMJ height in ACT (-1.9 ± 5.1 %) compared to PAS (1.8 ± 4.2 %). Since jump tests represent a valid means to monitor neuromuscular function in athletes, the current findings indicate a greater readiness to perform with PAS [36]. Moreover, jump performance seemed to be more adversely affected immediately after ACT in most cases, as compared to PAS. This was also accomplished by similar responses in markers of perceived PPC and MS (Figs 4-5). It is likely that the muscular activity in individualized submaximal rowing ergometer exercise may have led to an acute impairment in CMJ performance. This notion is corroborated by the jump performance increasing meaningfully immediately before each afternoon training session, particularly following the PAS intervention (Table 3). Neuromuscular performance shows diurnal variations with improved performance typically observed in the afternoon and evening compared with the morning [37]. This could be causally linked to similar circadian rhythm of the core temperature, peaking in the late after...
noon, and thereby inducing a passive warm-up effect that may improve muscle contractility. In addition both central (e.g., neural input to the muscles) and peripheral (e.g., contractile state of the muscles) mechanisms that could be altered across the day may also play an important role [37]. It has also been shown that strength training performed in the morning seemed to attenuate the circadian decline in free testosterone, and thus, potentiated neuromuscular performance (i.e., maximal strength, jumping power and sprint times) later in the day, suggesting a hormone-mediated effect on subsequent performance [38].

Regarding individual responses to the recovery interventions (Figure 6), two athletes showed positive responses to ACT. Subject #1 showed improvements in markers of sport-specific performance after the training period associated with higher ratings of perceived PPC and OR in ACT compared with PAS. For subject #3, ACT seemed to faster accelerate post-training recovery from training-induced fatigue, evidenced by a less pronounced drop in markers of sport-specific performance and a lower increase in perceived MS and OS after the training program, as compared to PAS. However, subject #8 appeared not to benefit from ACT with decreases in markers of sport-specific performance and increased rating of perceived MS and OS after the training program in ACT, as compared to PAS. Therefore it may be practically purposeful to adopt an individual-based approach to determine the effectiveness of ACT in the longer-term.

There are limitations to the present study that need to be considered. The two microcycles could not be precisely standardized, and therefore equated by volume, intensity and exercise selection, since athletes’ individual training protocols were exclusively designed by the national head coach, which were beyond our control. However, total training load and mean barbell load showed only trivial differences between the two microcycles as well as between the ACT and PAS modality (Figure 2). It may therefore be assumed that slight variations in training program design did not affect the outcome of this study. Furthermore, we are aware of the low sample size of the current study. However, this study was performed with a competitive high-quality sample, and given that there are not as many elite German Olympic weightlifters, increasing sample size was therefore almost impossible. Therefore we decided to report individual responses to the two recovery interventions analyzed in order to improve the decision-making process in terms of the effectiveness of ACT.

CONCLUSION

The repeated use of post-training ACT consisting of submaximal rowing ergometer exercise for 15 minutes had no beneficial or deleterious effects on the recovery pattern of sport-specific performance as well as on neuromuscular, physiological and perceptual markers of fatigue in elite German Olympic weightlifters during a 2-day high-intensity microcycle, as compared to PAS. In a short-term perspective, this may allow the application of ACT according to athletes’ and coaches’ individual preferences, experiences or beliefs. Additionally, if ACT is not being considered, practitioners should also be open to other recovery modalities to limit the severity of training-induced fatigue. However, this study provided evidence of variable individual responses to the recovery interventions, showing both beneficial and detrimental effects of ACT on performance. Therefore, the short-term implementation of an ACT program should be thoroughly considered at the individual level. In this regard, it may be also useful to closely monitor the athlete’s perceived recovery and stress status, since both measures appear to be sensitive for reflecting changes in sport-specific performance.

Future research, particularly in strength and power dominated sports, is required to evaluate the longer-term effects of ACT on physical and perceptual fatigue recovery, taking into account each athlete’s individual response.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DISCLOSURE OF FUNDING

The present study was initiated and funded by the German Federal Institute of Sport Science. The research was realized within RegMan — Optimization of Training and Competition: Management of Regeneration in Elite Sports (IIA1-081901/12-16). The authors would like to thank the coaches and athletes for their participation.

REFERENCES


ABSTRACT

Tensiomyography is used to measure skeletal muscle contractile properties, most notably muscle displacement (Dm) and contraction time (Tc). Professional football medical departments are currently using the equipment to profile the muscle function of their squad and subsequently evaluate change due to injury or intervention. However, at present there are no published standardised operating procedures for identifying probe position for muscle assessment. In this technical report we propose standardised operating procedures for the identification of precise probe position as part of an on-going study in male professional footballers.

KEY WORDS:
Muscle;
Tensiomyography;
Injury;
Football

A STANDARDISED PROTOCOL FOR THE ASSESSMENT OF LOWER LIMB MUSCLE CONTRACTILE PROPERTIES IN FOOTBALL PLAYERS USING TENSIOMYOGRAPHY

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INTRODUCTION

Tensiomyography (TMG) is a non-invasive technique used to measure the contractile properties of superficial skeletal muscles [1]. The technique, specifically contraction time (Tc), has previously been validated against muscle fiber type [2] and has been used to report the muscle contractile profiles of professional male football players [3,4,5]. TMG uses a probe containing a sensor to measure radial displacement (Dm) in response to electrical stimulation, which is a single biphasic pulsed electrical current delivered through surface electrodes at a rate of 1 millisecond [6]. The properties of muscle contraction, which can be estimated from the displacement-time curve, include contraction time (Tc), delay time (Td), sustain time (Ts), relaxation time (Tr) [7]. It is recommended that the probe is positioned perpendicular to the muscle belly, as this has suggested to be the largest cross sectional area of mass and the region for maximal fibre recruitment [1] and force production [8,9].

Measurement of Dm using TMG, has been reported to have excellent intra-session reliability (Intra-class correlation coefficient (ICC) >0.86) [10], between day reliability (ICC >0.95) [11] and inter-rater reliability (ICC 0.96-0.97) [7]. However, probe position has been largely based on operator anatomical knowledge or electromyography (EMG) reference points, for example the popliteal crease and measurements such as fingerbreadths for gastrocnemius muscle belly identification [3,4,5]. Inconsistencies in EMG electrode placement positioning have previously been reported [12] and therefore there is a need to standardise the approach taken to locate the muscle belly, in order to enable the comparison of muscle contractile parameters as measured by TMG.

The aim of this technical report is to describe a standardised protocol for probe placement in relation to superficial lower extremity muscles of professional football players.

METHODS

The following standard operating procedure was developed for use in ninety-eight healthy male professional football players during the pre-season period of the 2016/17 season. All players were free of musculoskeletal injury and had met the following inclusion criteria, which included no exercise for 48 hours and no caffeinated drinks 12 hours before testing. Each player was initially marked up using a dermatological pen; highlighting specific regions for muscle belly identification (Figure 1-6). A trained TMG operator, who had knowledge of anatomical landmarks and human muscle architecture, performed this initial procedure. The specific muscles selected for testing were rectus femoris, biceps femoris, adductor magnus, gastrocnemius medialis and gastrocnemius lateralis. These muscles have been reported to be the most commonly injured in previous injury surveillance data of male professional football [13,14]. The gluteus maximus was also tested because of the relationship between hip extensor contraction and hamstring injury risk [15,16]. The marking procedure for probe placement on the rectus femoris was adapted from Wilson et al [17] and similar reasoning was used to develop the procedure for all other muscles (Table 1).
### Table 1. Standardised protocol for probe position

<table>
<thead>
<tr>
<th>MUSCLE</th>
<th>PROTOCOL</th>
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| **Rectus Femoris**   | a) Locate two anatomical landmarks and mark with a dermatological pen  
|                      | i. Proximal point – greater trochanter  
|                      | ii. Distal end of the femur – lateral condyle  
|                      | b) Measure the distance between 2.a.i and 2.a.ii. along the vertical plane  
|                      | c) Using a dermatological pen, draw the transversal line at 50% of the total length (the muscle belly)  
|                      | d) Ask the participant to contract their quadriceps and palpate rectus femoris  
|                      | e) Using a dermatological pen, draw onto the skin the lateral and medial muscle boundaries.  
|                      | f) Using the transversal (2.c.), and lateral and medial muscle boundaries (2.e.), measure half way between the muscle boundaries and mark an ‘X’ on the transversal line.  
|                      | g) ‘X’ landmarks the most central point of the rectus femoris muscle belly which we can measure, and the point at which the TMG probe will be positioned. |
| **Biceps Femoris**   | a) Locate two anatomical landmarks and mark with a dermatological pen  
|                      | i. Proximal point – ischial tuberosity  
|                      | ii. Distal end of the femur – lateral condyle  
|                      | b) Measure the distance between 2.a.i and 2.a.ii. along the vertical plane  
|                      | c) Using a dermatological pen, draw the transversal line at 50% of the total length (the muscle belly)  
|                      | d) In a prone position, ask the participant to flex their knee, then resist and palpate rectus femoris  
|                      | e) Using a dermatological pen, draw onto the skin the lateral and medial muscle borders.  
|                      | f) Using the transversal (2.c.), and lateral and medial muscle boundaries (2.e.), measure half way between the muscle boundaries and mark an ‘X’ on the transversal line.  
|                      | g) ‘X’ landmarks the most central point of the bicep femoris muscle belly which we can measure, and the point at which the TMG probe will be positioned. |
| **Adductor Magnus**  | a) Locate two anatomical landmarks and mark with a dermatological pen  
|                      | i. Proximal point – pubic tubercle  
|                      | ii. Distal point – medial femoral condyle  
|                      | b) Measure the distance between 3.a.i and 3.a.ii. along the vertical plane  
|                      | c) Using a dermatological pen, mark measured point at 50% of the total length (the muscle belly)  
|                      | d) In a side-lying position, with the leg closest to the bed being marked, ask the participant to adduct their hip, then resist and palpate adductor longus  
|                      | e) Using a dermatological pen, draw onto the skin the lateral and medial muscle borders.  
|                      | f) Using the transversal (3.e.), and lateral and medial muscle boundaries (3.b.), measure half way between the muscle boundaries and mark an ‘X’ on the transversal line.  
|                      | g) ‘X’ landmarks the most central point of the adductor magnus muscle belly which we can measure, and the point at which the TMG probe will be positioned. |
| **Gastrocnemius Medialis** (Medial head) | a) Locate the widest girth of the lower leg (gastrocnemius muscle belly).  
|                      | b) Trace down from the medial border of the popliteal crease.  
|                      | c) In a prone position, ask the participant to plantarflex their ankle, then resist and palpate the gastrocnemius (medial head)  
|                      | d) Using a dermatological pen, draw onto the skin the proximal and distal muscle borders.  
|                      | e) ‘X’ landmarks the most central point of the gastrocnemius medial head muscle belly which we can measure, and the point at which the TMG probe will be positioned. |
| **Gastrocnemius Lateralis** (Lateral head) | b) Locate the widest girth of the lower leg (gastrocnemius muscle belly).  
|                      | c) Trace down from the lateral border of the popliteal crease.  
|                      | d) Using a dermatological pen, mark measured point where 2 measurements meet  
|                      | e) In a prone position, ask the participant to plantarflex their ankle, then resist and palpate the gastrocnemius (lateral head)  
|                      | f) Using a dermatological pen, draw onto the skin the proximal and distal muscle borders.  
|                      | g) ‘X’ landmarks the most central point of the gastrocnemius lateral head muscle belly which we can measure, and the point at which the TMG probe will be positioned. |
| **Gluteus Maximus**   | a) Locate two anatomical landmarks and mark with a dermatological pen  
|                      | i. Proximal point – Right or left Posterior Superior Iliac Spine  
|                      | ii. Distal point – Ischial Tuberosity  
|                      | b) Measure the distance between 3.a.i and 3.a.ii. along the transverse plane  
|                      | c) Using a dermatological pen, mark measured point at 50% of the total length (the muscle belly)  
|                      | d) In a prone position, ask the participant to extend their hip, then resist and palpate the gluteus maximus  
|                      | e) ‘X’ landmarks the most central point of the gluteus maximus belly which we can measure, and the point at which the TMG probe will be positioned. |
DISCUSSION

This report details a new standard procedure for muscle belly identification i.e. probe placement on selected lower limb muscles related to football injury. As described in the methods, identification of the muscle belly was performed by measuring the length of the muscle; a common method reported in previously published studies [7,11]. The newly developed protocol measures muscle width from the borders of the muscle identified from a manually resisted isometric contraction in order to identify the muscle belly. This enhances the possibility of obtaining DM not just from the midpoint of the muscle, but from the muscle belly itself. This approach proved straightforward for the rectus femoris, biceps femoris, adductor magnus and gluteus maximus muscles as the midpoint of the muscle is between its origin and insertion, as is also the area of largest contractile mass [18, 19]. However, in the case of gastrocnemius, where the muscle belly is located more proximal to its origin, a different approach was required. Instead, the widest girth of the calf was identified in accordance with procedures used for the measurement of skinfolds [20].

CONCLUSION

We propose the use of the described standardised TMG protocol for the measurement of selected lower limb muscles in male professional football players, particularly for repeat measures multiple operator use. Future research measuring the intra and inter-rater reliability of TMG measures would be of value to further establish the efficacy of the protocol within clinical and research practice.

REFERENCES

ABSTRACT

The purpose of this study was to use TMG for the assessment of lateral symmetries (LS) and muscle response speed (Vrn) in elite futsal players in accordance with the specific position of the players. A total of 23 male elite futsal players competing in the Spanish elite championship were assessed. Five muscles were analysed: biceps femoris (BF), rectus femoris (RF), semitendinosus (ST), vastus lateralis (VL), and vastus medialis (VM). All assessments were carried out during the same period (i.e., in-season competition and on the recovery day of the microcycle). An analysis of variance of one factor for playing position and for muscle factor were performed on the parameter obtained (Vrn) for BF, RF, ST, VL, and VM. Cohen’s $d$ effect sizes were used to identify statistical differences. The results show that there are no muscle function differences between the dominant and non-dominant limb and no differences in lateral symmetries between muscles. Many differences were found between muscles but very few ones were found between playing positions. In conclusion, Vrn seems to be a useful parameter to assess the neuromuscular characteristics of the knee extensor and flexor musculature in futsal players during the season.
INTRODUCTION

Futsal (IS) (the official name for five-a-side indoor soccer) is an intermittent high-intensity team sport that requires high physical, technical, and tactical demands. One of the major differences between this sport and its older version, the outdoor soccer, is that it is played on a smaller space (38-42 x 18-25 m). This places a higher emphasis on sprints, rapid changes in direction and fast decision making related to the technical and tactical actions. Therefore, this sport is characterized by fractional physical efforts with incomplete active and passive recovery of variable duration [1] and greater number of high-intensity sprints than in other team sports [2]. As in other team sports (e.g., soccer or volleyball), the morphological, muscular and conditional differences between playing positions may become the critical qualitative variables in the performance and predisposition to injury [3,4]. The extant literature on the incidence of injuries in team sports reports that the greater activation of the hamstrings observed during braking actions and/or coactivation (i.e., between the flexor and extensor muscles of the knee joint) when sprinting or changing direction are the main factors predisposing a player to an injury [5-8].

In addition, muscle imbalances caused by the relative lack of strength and flexibility have also been associated with the risk of injuries in team sports [9,10]. It is therefore important for coaches and physical trainers to have methods to detect possible muscle imbalances to predict the injury risk, especially in the muscles maximally loaded in this sport (i.e., knee extensors and flexors). In accordance with the specific demands of each position [11, 12], precise and individualized evaluations should be performed to prevent injuries. To evaluate the neuromuscular state of the players, many coaches have resorted to the use of different tests as the repeated sprint ability [13], change of direction ability [14] or traditional tests as the countermovement jump [15]. However, this is not always possible during the season since it takes a lot time or such tests are assumed to be added load to the training that may affect the distribution of planned load of the microcycles [16]. Therefore, methods to perform quick and non-invasive measurements on the neuromuscular functions need to be explored.

Tensiomyography (TMG) is a non-invasive diagnostic technology used to assess the functional properties of the skeletal muscles [17]. The TMG-generated parameters can detect imbalances between muscles and/or limbs [18], evaluate the neuromuscular status [19], and assess muscle fatigue [20]. The output data of the TMG consists on several parameters as muscle belly displacement (Dm), contraction time (Tc), delay time (Td), sustained contraction time (Ts) and relaxation time (Tr) [21]. In addition, a TMG derived-parameter termed as normalized response speed or response speed (Vm) has been used to report genders differences in knee extensors and flexors of professional volleyball players [22]. Vm has also been used to analyse differences in muscle response and mechanical characteristics of several muscles in elite volleyball players [23], and to assess the effects of age and physical activity on response speed of the knee joint [24]. Rodríguez-Ruiz et al. [24] found differences for the vastus lateralis but not for biceps femoris between subjects of different range of ages and levels of physical activity. Thus, the use of this parameter allows avoiding possible imbalances due to the morphological and functional differences and demands of the players.

Based on the usefulness of Vm to assess the responses and mechanical characteristics of skeletal muscles and considering the differences between futsal and outdoor soccer, the objectives of this study were: (1) to use TMG for the assessment of lateral symmetries (LS) and Vm differences between dominant and non-dominant knee extensors and flexors in elite futsal players; and (2) to analyse the response speed of these muscles in accordance with the specific position of the players. Thus, we hypothesized that: (1) there would be significant differences between dominant and non-dominant knee extensors and flexors in elite futsal players; and (2) there would be adequate LS between muscles; and (3) there would be significant differences in the response speed of these muscles in accordance with the specific positions.

METHODS

Participants

23 male elite futsal players competing in the Spanish elite championship (First Division, rank 1 of the Union of European Football Associations) participated in the study. The participants had a minimum of one and a maximum of 15 years history of playing professional senior futsal. Participants’ characteristics are shown in Table 1. Only the players free from any injury were tested. The participants and coach were informed in detail about the experimental procedures and the possible risks and benefits of the study and provided written informed consent. The experimental protocol followed the Declaration Helsinki of World Medical Association for research with humans.

<table>
<thead>
<tr>
<th>Table 1. Participant characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Goalkeeper (n = 4)</td>
</tr>
<tr>
<td>Defender (n = 6)</td>
</tr>
<tr>
<td>Winger (n = 8)</td>
</tr>
<tr>
<td>Pivot (n = 6)</td>
</tr>
<tr>
<td>All (n = 24)</td>
</tr>
</tbody>
</table>
The players were classified in four positional groups [11]: goalkeepers (G, n = 4), defenders (D, n = 6), wingers (n = 8), and pivots (n = 6). Before each testing session, players were advised to: (1) not to take part in any strenuous exercise 48 h before testing; (2) not to consume any energy/performance-enhancing drinks or supplements 48 h before testing; (3) not to take beverages containing caffeine or alcohol at least three hours before testing; and (4) not to consume food at least 2 h before testing. Leg dominance was determined by asking the participants which leg they would use to kick a ball.

Measurement Procedures

All assessments were carried out during the same period (i.e., in-season competition and during the recovery day of the microcycle). Five muscles were analysed by TMG: the biceps femoris (BF), the rectus femoris (RF), the semitendinosus (ST), the vastus lateralis (VL), and the vastus medialis (VM). Leg dominance nomenclature was established as: dominant and non-dominant (biceps femoris - DBF and NDDBF, rectus femoris - DRF and NDRF; semitendinosus DST and NDSST; vastus lateralis - DVL and NDVL; and vastus medialis – DVM). These are the most significant muscles involved in the physical and technical actions in futsal [12]. A pressure digital transducer (GK 40, Panoptik d.o.o., Ljubljana, Slovenia) was attached to the belly of the selected muscle, ensuring that it was positioned perpendicular to the muscle. Sensor location was determined anatomically according to Delagi et al. [25]. Both electrodes (5 × 5 cm) were placed following the instructions of García-García et al. [26]. Measurements were performed in supine position for RF, VL, and VM and in prone position for BF and ST, both set at 30º angle of knee flexion. To provoke muscle contraction, a bipolar electrical current (1 ms and amplitude of 30 mA), was progressively applied with increments of 10 mA until maximal stimulator output was reached. A 10s rest between subsequent electrical stimuli was set to avoid the phenomenon of post-tetanic activation [27].

All measurements were made by the same researcher, who was experienced in taking these measurements. In the present study, Vrn was registered (Figure 1). The equation of this parameter has been stated in other studies [22]:

$$V_r = \frac{\Delta d_r}{\Delta t_c} [mm/s]$$  \hspace{2cm} (1)

$$V_n = \frac{V_r}{D_m} = \frac{\Delta d_r/\Delta t_c [mm/s]}{mm/mm}$$  \hspace{2cm} (2)

$$V_{rn} = \frac{0.8}{t_c} [mm/s]$$  \hspace{2cm} (3)

where Vrn is the normalized speed response (Eq. 3), Δdr is the maximal amplitude of the muscle response while Δtc represents the increase in muscle contraction time between 10% and 90% of the muscle response. Moreover, Vr is the speed response without normalization and the 0.8 is a constant value. The reproducibility and the validity of this method has been assessed by several authors [27-29]. The reliability and degree of error [30] of the parameter included in the Vrn equation (Tc) were also tested in the present study for all the assessed muscles in a randomized sample of the participants (n = 8).

RESULTS

No significant differences were found in the muscle function parameters of all the assessed muscles between the dominant and non-dominant leg (Table 2).
There were also no significant intra-participant or between-muscles differences in LS (Figure 2). VM showed the highest LS values (90.58 ± 4.21%) while BF showed the lowest (84.13 ± 6.2%).

Since there were no between-muscles differences in LS, summation of both legs was done to analyse differences between muscles and playing positions. In this regard, only significant differences were found in RF between the winger and goalkeeper position with a large effect size (31.3 Vs 24.88 m/s; 25.8%; p=0.013).

Vrn was different between all muscles (range 10.1-42.9%; p≤0.01) with a moderate-large effect size (ES range 0.74-3.0) except between BF and RF (p=0.762). The maximum difference between muscles was found in ST and VL (42.9%; 21.1 Vs 37 mm/s) and the least between VL and VM (10.1%; 37 Vs 33.6 mm/s). The VL and VM showed the same Vrn behaviour with different values (± 11 mm/s) between positions, both being the muscles that presented the lowest values of Vrn in comparison with the other muscles. In addition, the ST presented the lowest values of Vrn whereas the VL showed the highest (Figure 3).

<table>
<thead>
<tr>
<th>Muscle</th>
<th>D-Vrn</th>
<th>ND-Vrn</th>
<th>D-Vrn vs. ND-Vrn (p-value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biceps Femoris</td>
<td>29.91</td>
<td>28.27</td>
<td>0.28</td>
</tr>
<tr>
<td>Rectus femoris</td>
<td>28.33</td>
<td>28.81</td>
<td>0.64</td>
</tr>
<tr>
<td>Semitendinosus</td>
<td>20.86</td>
<td>21.49</td>
<td>0.40</td>
</tr>
<tr>
<td>Vastus Lateralis</td>
<td>36.29</td>
<td>37.85</td>
<td>0.10</td>
</tr>
<tr>
<td>Vastus Medialis</td>
<td>33.93</td>
<td>33.27</td>
<td>0.34</td>
</tr>
</tbody>
</table>

**DISCUSSION**

We hypothesized that there would be differences in LS, leg dominance and between muscles and playing positions regarding the response speed of elite futsal players. Although other studies have previously described the response speed of another team sport [23, 24] (i.e., volleyball), this is seemingly the first study to investigate the behaviour of the response speed between muscles and playing positions in elite futsal. Contrary to our hypothesis, the results showed: (1) no muscle differences between dominant and non-dominant limb and (2) no differences in lateral symmetries between muscles. In addition, many differences were found between muscles but very few differences were found between playing positions. Furthermore, the response speed (i.e., Tc) showed an acceptable level of intra-class correlation and low-to-moderate degree of error (i.e., coefficient of variation) for all muscles. Differences in the various TMG parameters between dominant and non-dominant limbs in professional soccer players has been previously reported [31-32]. García-Garcia et al [31] showed different results regarding Tc (i.e., non-normalized Vrn) with no differences between knee extensor and flexor muscles whereas Gil et al [32] reported the opposite. Our results are in line with García-Garcia et al [31] with no differences found in leg dominance in all the muscles assessed. As futsal is a sport of reduced space and rapid changes between sides of the field, our findings suggest that there are no limb dominance-based differences, regardless of the position in the field, and all the
positions have similar demands [1] excepting the goalkeeper. Some authors [33-34] have suggested that lateral asymmetry of a same muscle group (e.g., dominant ST vs. non-dominant ST) may be linked to muscle injury risk. In the current study, elite futsal players presented similar LS in all the muscles assessed without significant between-muscle differences. Of the muscles assessed, only the BF presented values close (84.13 ± 1.27%) to that (<75%) considered as risk of injury. The BF muscle is involved in several intrinsic actions in futsal (e.g., acceleration, sprinting, shooting) and is the most commonly injured muscle in soccer [5-8]. Our results showing lower BF LS is of practical value to coaches, fitness and the medical staff who should address the specific muscle functions to increase BF LS and minimize the occurrence of an injury. As TMG can quickly and non-invasively measure LS, periodic assessment of LS might be worthwhile to avoid injuries. As none of the participants in this study were injured, our findings are in line with those found by Gil et al. [32] that lateral dominance in soccer does not contribute to asymmetries in soccer players’ knee extensor and flexor muscles. Based on our results, the same holds true in elite futsal players.

In our study, few differences in muscle response speed were found between positions (Winger and Goalkeeper, 31.3 vs 24.88 m/s; 25.8%; p=0.013). However, many differences were found between muscles. These large and significant differences could be explained based on the architectural differences between the knee extensors and flexors (i.e., pennation angle, fiber composition or fiber orientation) [36-38]. Studies reporting response speed differences between playing positions and the knee extensor and flexor muscles have been carried out in volleyball [23-24]. This makes comparisons improbable as futsal and volleyball are different categories of team sports with different technical and tactical demands.

In terms of reliability, two intra-session studies [21,39] found a good to excellent level reliability for both BF and RF. The reliability results for the muscles assessed in the present study were similar to those reported in the aforementioned studies. Moreover, we also assessed the ST, VL, and VM muscles which also showed an acceptable level of reliability. Although the assessed muscles presented an acceptable level of reliability, some muscles presented moderate scores of CV (i.e., BF and ST). Taken together, our findings are valuable for practitioners, as impairments in TMG response have been shown to be related to risk factors for knee injuries [18]. However, based on recent reports [32], caution should be exercised in the interpretation and generalization of our results as TMG has not yet been validated against gold standard methods of measures of muscle contraction conduction/velocity (e.g., surface electromyography).

CONCLUSIONS

TMG is a simple, non-invasive and useful tool to assess the neuromuscular characteristics of the knee extensor and flexor musculature in intermittent sports like futsal. Many significant differences were observed between muscles but very few according to positional role in VM parameter. Future studies should investigate the nature of the relationship between TMG parameters and the identification of potential predictors of performance in elite futsal. It is also desirable for the studies to adopt a longitudinal design with a larger sample size to gain further insights in this area.

CONFLICT OF INTEREST

The authors report no potential conflict of interest.

REFERENCES


ABSTRACT

This study aimed to measure contractile rate of torque development (RTD) from maximal voluntary isometric contractions (MVC) of the knee extensors and flexors in order to determine reliability of the measure, report age-related difference in RTD, determine the association between RTD and selected functional tasks and determine the effect of progressive resistance training (PRT) on RTD in healthy 50-70y women. 136 women performed MVC’s of the knee extensors and flexors. Maximal RTD was determined from the slope of the most linear phase of the torque-time trace. RTD was also determined at 0-50 ms; 0-100 ms and 0-200 ms from the onset of contraction in a subsample (n=26) of knee extensor MVC’s. Functional capability was determined based on the ability to complete a 900 m gait speed test (n=128) and the number of chair rises completed in 30 seconds (n=68). 57 participants were randomised into a protein supplementation (PRO) control group or a PRO + PRT group for 12 weeks. Maximal RTD had a coefficient of variance of ≤ 17%. RTD became more dependent on maximal strength as the time from the onset of contraction increased as did its association with maximal RTD. On average, participants in the 7th decade of life had a lower (~23%; \( P < 0.01 \)) RTD than their younger counterparts in the 6th decade. RTD had a weak association with extended gait speed (\( r = -0.234; P=0.008 \)) and was not associated with chair rise performance (\( r = 0.076; P=0.540 \)). RTD did not change in response to 12 weeks of PRT and PRO compared to a PRO only group (+9% vs. +13%; \( P > 0.05 \)). Maximal RTD cannot be measured reliably in healthy 50-70 year old women from the most linear slope of the torque-time trace of an isometric MVC. Age-related difference in maximal RTD appears to be greater than that of maximal strength. Maximal RTD has a weak association with functional capability and does not change in response to PRT in healthy 50-70 year old women.

KEY WORDS:
- Speed of contraction;
- Muscle function;
- Torque;
- Ageing

VOLUNTARY CONTRACTILE RATE OF TORQUE DEVELOPMENT IN HEALTHY 50-70 YEAR OLD WOMEN: MEASUREMENT OF, ASSOCIATION WITH FUNCTIONAL TASKS AND RESPONSE TO AN INTERVENTION

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INTRODUCTION

Epidemiological studies on ageing have routinely collected data on lower extremity muscle or lean tissue mass (LTM) and maximal voluntary strength [1-3]. These laboratory assessed components of muscle health are thought to be central to the diagnosis of sarcopenia and associated functional disability [4]. However, the age-associated decline in the speed of muscle contraction has been reported to be greater than that of muscle strength [5-8] particularly in women [9,10]. Therefore, measurement of the speed of muscle contraction may provide a more sensitive measure of physiological changes in muscle prior to disability. Moreover, the ability to perform functional tasks depend on both torque production and the speed of contraction [11]. In fact, Sayers and colleagues [12] reported leg muscle contraction velocity but not muscle strength to be associated with gait speed in community dwelling older women (75 – 90y).

The challenge in reporting age-related difference in the speed of muscle contraction and its association with functional capability is the ability to measure it. To date, the ability to rapidly generate muscular force has been measured using mixed methodologies and as of yet there is no criterion method. Studies have measured rate of force development (RFD) [13,14], power [6] or compared age-related changes in slow (0°/s - 60°/s) and fast (>60°/s) isokinetic strength measurements. As such, there is no criterion reference range from which change due to ageing or intervention can be evaluated.

Contractile rate of force development (RFD) is a term used to describe the rate at which an individual can rapidly generate muscular force. The work of Andersen and Aagaard [13,14] has confirmed that in vivo contractile RFD can be measured in young adults from the slope of the torque-time curve obtained during isometric conditions. The potential to measure maximal voluntary strength and simultaneously obtain a measure of the intrinsic contractile ability of muscle is attractive in research with older adults. Isometric contractions are easy to administer, require less habituation than isokinetic measures and are time efficient for generating information on large data sets across age ranges [15].

The University of Limerick Healthy Ageing Study [3,16,17] measured peak isometric torque from MVC’s of the knee extensors and flexors in healthy older adults. The purpose of these contractions was a) to report age-related difference in maximal voluntary strength and muscle quality between the 6th and 7th decade of life; b) to determine the association between lower extremity maximal voluntary strength and selected functional tasks and c) to act as a baseline measure of maximal voluntary strength prior to dietary and/or exercise interventions. This investigation reports the contractile rate of force development based on secondary analysis of these isometric contractions.

To the best of the author’s knowledge it is not yet known whether contractile rate of torque development (RTD) can be measured reliably from the most linear phase of a torque-time trace generated from a MVC in healthy older women. Furthermore, it is unclear whether voluntary RTD follows the same trajectory at 0-50ms, 0-100ms and 200ms as that reported previously in young adults [12]. Therefore, the aims of this research were to: a) determine reliability of the measure b) report age-related difference in RTD c) determine the association between RTD and selected functional tasks and d) determine the effect of PRT on RTD in a convenience sample of healthy 50 -70 year old women.

MATERIALS AND METHODS

136 healthy women (age range: 50 -70y) were recruited as part of the University of Limerick Healthy Ageing Study [3,16,17]. Participants were screened by a physician and provided a full medical history. Those defined as healthy, i.e. disease free based on Greig et al. [18], independent-living, fully mobile and with no indication of dairy or lactose intolerance were invited to participate and to provide written informed consent. Height was measured to the nearest 0.1cm (SECA stadiometer) and body mass (BM) was measured to the nearest 0.1kg (MC-180MA; Tanita UK Ltd.). 136 women performed MVC’s of the knee extensor and flexor muscle groups. 128 and 68 participants completed a 900 m gait speed test and a 30 second chair rise test respectively. 57 of the participants were randomised into a control group (n=28; protein supplementation (PRO) only) or a progressive resistance training (PRT) + PRO group (n=29). All procedures were performed in accordance with the most recent version of the Declaration of Helsinki. The University of Limerick Healthy Ageing Study was approved by the Research Ethics Committee of the Faculty of Education and Health Sciences Research Ethics Committee (EHREC 10/45). The trial was registered at clinicaltrials.gov as NCT02529124.

ASSESSMENT OF A MAXIMAL VOLUNTARY CONTRACTION

Procedures for the assessment of a MVC have been reported in detail in our recently published manuscript [2]. Briefly, participants were tested during two identical sessions held 7 days apart in order to reduce potential learning effects. Warm up consisted of 5 min on a bicycle ergometer (Monark Ergomedic; 828E, Monark Exercise AB, Vansbro, Sweden) at a workload of 40 watts. The knee extensors and flexors of the dominant limb (the limb used to kick a ball) were tested using a commercially available dynamometer (Con-Trex M1; CMV AG, Dubendorf, Switzerland) which allows instantaneous isometric torque assessment. Participants were seated with a hip flexion angle of 110°. The back of the knee joint was on the edge of the seat with a knee angle of 60° from anatomical zero (180°), which has been demonstrated to be the angle of maximal isometric force generation [19]. Participants were instructed to perform two submaximal voluntary isometric contractions (50% and 75% of perceived maximum) prior to each test series similar to Maffioletti et al. [20] interspersed with a 1-min rest period. The participant then performed 3 MVC’s separated by 2 min of stationary rest. All measures were repeated separated by seven days in order to reduce potential learning effects.

Criteria for Acceptance of a Maximal Voluntary Contraction

A MVC produced a measure of isometric peak torque in a single effort which required >200 ms and was sustained for
~250 ms. Attempts not sustained for MVC (identified by an impact spike prior to 300 ms), containing an initial countermovement (identified by a visible drop/rise in the torque signal) >5N.m or with a nonlinear time-torque trace (identified by a double movement) were disqualified and excluded from further analysis.

**ANALYSIS OF CONTRACTILE RATE OF TORQUE DEVELOPMENT**

*RTD from the Linear Phase of the Torque-Time Trace*

Data was exported to Microsoft Excel and the torque-time trace smoothed with a 0.1s moving average to minimise any false traces due to noise [7]. As the Con-Trex MJ dynamometer samples at a rate of 256 Hz, it provides data on torque every 0.003906 seconds. This allows the user to create a time column in seconds for every data point. The first MVC occurs ~150 seconds into data recording. A selection of ~100 torque-time data points are selected from just before the onset of contraction to just after MVC. Using the line function in Microsoft Excel, the most linear slope of the line was identified (Figure 1). These points are then used to calculate the slope of the line i.e. the RTD.

![Figure 1: Analysis of RTD from a maximum voluntary contraction of the knee extensors](image)

**RTD at Different Time Points**

26 contractions of the knee extensors underwent analysis of RTD at 3 different time points after the onset of contraction (0-50 ms; 0 – 100 ms; 0 – 200 ms). Five seconds prior to the onset of muscle contraction was identified. The difference between adjacent data points in the lead up to the onset of contraction were identified in a separate column. The average of the difference between adjacent points was calculated and multiplied by 5 to obtain the point at which torque rises 5 times above baseline. From the identified baseline the slope of the torque-time curve (i.e. \(\Delta\)torque/\(\Delta\)time) was calculated from the first 13 data points (i.e. 0-50ms), 26 data points (0-100 ms) and 52 data points (0-200 ms).

**Functional Tasks**

The ability to rise from a chair was assessed by counting the number of chair rises completed in 30 seconds [21]. Maximal extended gait speed (n=128), using a one or a combination of walking, jogging or running, was assessed by the time taken to complete 900 m (4 laps of a 225 m indoor track) [16,17]. All measures were repeated separated by 7 days in order to reduce the potential for a learning effect. All measurements were conducted by the same exercise scientist to exclude issues with inter-tester reliability.

**Dietary Protein Supplementation and Progressive Resistance Training**

Assessment of habitual dietary protein intake and dietary protein supplementation has been described in detail in our recently published manuscript [22]. Briefly, dietary analysis and regulation of supplement intake was undertaken by a registered dietician. Participants had habitual dietary intake assessed using a 4-day food diary encompassing two week days and two weekend days. Food intake data were coded and subsequently analysed using WISP® (Tinuviel Software, Anglesey, UK). Participants were instructed to take a supplement at their two smaller protein containing meals of the day i.e. typically breakfast and lunch. Sachets were provided in powder format and could be mixed with water to make-up a powdered beverage or incorporated into meals. Supplements were prescribed relative to the median 4 levels of participants’ body mass (BM) i.e. 45-59.9 kg, median of 52.5 kg; 60-74.9 kg, median of 67.5 kg; 75-89.9 kg, median of 82.5 kg and 90-105 kg, median of 97.5 kg). Each supplement dose provided 0.165 g protein ·kg⁻¹ ·BW⁻¹ ·d⁻¹ of median BM.

Supervised (qualified sport and exercise scientist or chartered physiotherapist) PRT was performed on three non-consecutive days of week at a University sports hall. Each session lasted 45-60 minutes and consisted of a warm up, PRT and a cool down. Participants were provided with equipment (aerobics step and therabands) and while they had the option of performing a maximum of two of the sessions at home, most preferred to attend. The first three weeks of the programme had an emphasis on ensuring the correct exercise technique and monitoring the appropriate amount of exercise and rest intervals for each individual. Between weeks 3 and 12, the programme was designed to promote muscle hypertrophy (4-6 sets, 8-15 repetitions) as recommended by Bird et al. [23]. The PRT programme consisted of a number of upper and lower body exercises using therabands (T) and body weight (BW) as the primary resistance. The primary exercises used throughout the program included squats (T), lunges (T), hip abduction (T), shoulder press (T), latissimus dorsi pull-down (or seated row) (T), bicep curls (T), calf raises (BW), push ups (BW), tricep dips (BW) and lumbopelvic stabilisation exercises.
STATISTICAL ANALYSIS

For parameters of muscle function, within and between participant reliability was calculated using the coefficient of variance (CV) and intra-class correlation (ICC) respectively. Data were checked for normality of distribution by using the Komolgorov-Smirnov and Shapiro-Wilk tests and expressed as means ± SDs (95% CI) for normally distributed variables and medians (IQRs) (Q1-Q3) for non-normally distributed variables. Linear regression was used to determine the variance in RTD explained by peak torque and the variance in the linear phase of RTD explained by RTD at different time points. An independent samples t-test was used to report age-related difference in voluntary RTD. Pearson’s r was used to report the association between linear phase RTD and performance in functional tasks. The treatment effect was calculated as the change in outcome measure from baseline to 12 week and presented as mean change and relative percentage change. These data were analysed by univariate ANOVA with treatment (PRO compared with PRO + PRT) as a fixed factor. To determine the influence of baseline RTD on the changes seen at 12 week, data were analysed by ANCOVA with group as a fixed factor and baseline RTD as the covariate. Baseline dietary intake and compliance to the dietary protein supplement were also used as co-variates to determine their effects on changes in RTD. Statistical analysis was performed by using PASW Statistics 22.0 for Windows (IBM SPSS, Inc.). Significance (2-tailed) was set at P < 0.05 for all analyses.

RESULTS

Physical characteristics for participants are displayed in Table 1. Reliability of estimate for peak torque measured from a MVC was excellent. Measurement of contractile RTD from the most linear slope of the torque-time trace could not be measured reliably nor could time to peak torque (TTPT) (Table 2). Normalised for body mass, maximal knee extensor strength explained ~38% of the variance in maximal voluntary RTD. Peak isometric torque of the knee extensors was associated with voluntary RTD at time points ≥100 ms after the onset of contraction. The association between maximal RTD and RTD at different time points became stronger as time increased from the onset of contraction (Table 3). Age-related differences are reported from participants who produced repeated measures of maximal knee extensor RTD (n=97) and knee flexor RTD (n=105) within a coefficient of variance of 10% or who had a single maximum RTD identified. In this sample the coefficient of variance improved to 4% for the knee extensors and flexors and the intra-class correlation coefficient improved to 0.990 and 0.986 respectively. On average, those in the 7th decade demonstrated a reduction in RTD in both the knee extensors and flexors (P≤0.01; Table 4). Maximal knee extensor RTD had a weak association with extended gait speed (r=-0.234; P=0.008) and no association with the number of chair rises completed in 30 seconds (r=0.076; P=0.540). Maximal knee extensor RTD did not change in response to 12 weeks of PRT (Table 5).

Table 1. Physical characteristics of the participants (female; healthy; age range 50-70 years).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>60.2 ± 5.2</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>162.1 ± 5.5</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>70.2 ± 12.9</td>
</tr>
<tr>
<td>BMI kg/m²</td>
<td>26.8 ± 5.0</td>
</tr>
</tbody>
</table>

Table 2. Reliability of estimate for torque and rate of torque development (RTD).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean ± SD</th>
<th>CV (%)</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Extensor Torque (N•m)</td>
<td>84 ± 24</td>
<td>3</td>
<td>1.000</td>
</tr>
<tr>
<td>Knee Flexor Torque (N•m)</td>
<td>45 ± 12</td>
<td>3</td>
<td>0.993</td>
</tr>
<tr>
<td>Knee Extensor RTD (N•m•s⁻¹)</td>
<td>422 ± 187</td>
<td>17</td>
<td>0.840</td>
</tr>
<tr>
<td>Knee Flexor RTD (N•m•s⁻¹)</td>
<td>258 ± 104</td>
<td>14</td>
<td>0.768</td>
</tr>
<tr>
<td>Knee Extensor Time to Peak (s)</td>
<td>0.94 ± 0.47</td>
<td>25</td>
<td>0.067</td>
</tr>
<tr>
<td>Knee Flexor Time to Peak (s)</td>
<td>0.88 ± 0.51</td>
<td>24</td>
<td>0.083</td>
</tr>
</tbody>
</table>

Table 3. The association between RTD at different time points, peak torque and the linear phase of the torque time curve (n=26).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean ± SD</th>
<th>Peak Torque (N•m)</th>
<th>RTD Linear Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r² (p-value)</td>
<td>r² (p-value)</td>
<td></td>
</tr>
<tr>
<td>Knee Extensor RTD 0 – 50 (N•m•s⁻¹)</td>
<td>263 ± 146</td>
<td>0.002 (0.848)</td>
<td>0.289 (0.006)*</td>
</tr>
<tr>
<td>Knee Extensor RTD 0 – 100 (N•m•s⁻¹)</td>
<td>398 ± 168</td>
<td>0.221 (0.018)*</td>
<td>0.585 (&lt;0.001)*</td>
</tr>
<tr>
<td>Knee Extensor RTD 0 – 200 (N•m•s⁻¹)</td>
<td>390 ± 150</td>
<td>0.701 (&lt;0.001)*</td>
<td>0.627 (&lt;0.001)*</td>
</tr>
</tbody>
</table>
DISCUSSION

The first significant finding from this study was that maximal RTD as measured from the linear phase of the torque-time trace of an isometric MVC demonstrated poor within-participant reliability in healthy older women. RTD increased with time from the onset of contraction (0-200 ms) and became increasingly more dependent on maximal strength as the time from contraction increased. Maximal RTD was associated with RTD at all time points (0-50ms; 0-100ms; 0-200ms) and this association increased as the time from onset of contraction increased. Normalised to body mass, knee extensor torque explained 38% of the variance in maximal RTD (Figure 2). On average, those in the 7th decade of life had lower (~23%) RTD compared to their younger counterparts in the 6th decade. Maximal knee extensor RTD had a weak association with extended gait speed and was not associated with chair rise performance. Maximal RTD did not change in response to PRT and PRO supplementation.

The variability in the measurement of contractile RTD from MVC’s in which peak torque can be measured within an error of 3% is interesting. To explain whether the variance is arising from age-related difference in motor output variability or the method for determining RTD is challenging. It has been reported that older adults exhibit greater motor output variability [24-26]. Jakobi and Rice [26] reported no difference in central activation between younger and older adults when compared to their single best trial, however, when central activation was compared over 10 trials, a dramatic age-difference was observed (79 vs. 95% activation). Compared to young men who had knee extensor voluntary RFD assessed 200 ms after the onset of contraction [13], there is greater variability around the mean in our sample of older women (842 ± 224 N·m·s⁻¹ vs. 422 ± 187 N·m·s⁻¹). The variability between groups is less in the assessment of MVC (211 ± 49 N·m vs. 84 ± 24 N·m). This would be consistent with a hypothesis that older adults are capable of maximal muscle recruitment which is reproducible but the speed of muscle contraction is more variable. In addition to an increase in older adult motor output variability, it should be acknowledged that the method for determining maximal RTD from an isometric contraction does require the subjective positioning of a line through the most linear phase and may also contribute to the variability of the measurement. We determined RTD at different time points from a sample (n=26) of knee extensor contractions in order to be able to make some comparisons with the data of Andersen and Aagaard [13]. This process involves using a standardised criteria to determine the onset of contraction before assessing ∆ torque / ∆ time i.e. RTD at specified time points. This procedure removes the subjective positioning of a line through the most linear phase of the torque-time trace which may also contribute to the variability of the measurement. We determined RTD at different time points from a sample (n=26) of knee extensor contractions in order to be able to make some comparisons with the data of Andersen and Aagaard [13]. This process involves using a standardised criteria to determine the onset of contraction before assessing ∆ torque / ∆ time i.e. RTD at specified time points. This procedure removes the subjective positioning of a line through the most linear phase of the torque-time trace which may also contribute to the variability of the measurement. We determined RTD at different time points from a sample (n=26) of knee extensor contractions in order to be able to make some comparisons with the data of Andersen and Aagaard [13]. This process involves using a standardised criteria to determine the onset of contraction before assessing ∆ torque / ∆ time i.e. RTD at specified time points. This procedure removes the subjective positioning of a line through the most linear phase of the torque-time trace which may also contribute to the variability of the measurement. We determined RTD at different time points from a sample (n=26) of knee extensor contractions in order to be able to make some comparisons with the data of Andersen and Aagaard [13]. This process involves using a standardised criteria to determine the onset of contraction before assessing ∆ torque / ∆ time i.e. RTD at specified time points. This procedure removes the subjective positioning of a line through the most linear phase of the torque-time trace which may also contribute to the variability of the measurement.

![Figure 2. The relationship between maximal voluntary RTD and MVC.](image)

### Table 4. Age-related difference in RTD for healthy older women.

<table>
<thead>
<tr>
<th></th>
<th>50 – 59y</th>
<th>60 – 70y</th>
<th>Δ</th>
<th>Δ%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Extensor RTD (N·m·s⁻¹) 95% CI</td>
<td>516 ± 188</td>
<td>369 ± 198</td>
<td>147±52; P&lt;0.001</td>
<td>28</td>
</tr>
<tr>
<td>Knee Flexor RTD (N·m·s⁻¹) 95% CI</td>
<td>273 ± 103</td>
<td>226 ± 105</td>
<td>47 ± 18; P=0.010</td>
<td>17</td>
</tr>
</tbody>
</table>

### Table 5. RTD changes in response to 12 weeks of PRO and PRO +PRT.

<table>
<thead>
<tr>
<th></th>
<th>Baseline (N·m·s⁻¹)</th>
<th>Δ (N·m·s⁻¹)</th>
<th>Δ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Extensor RFD 95% CI</td>
<td>421 (329)</td>
<td>21 ± 168</td>
<td>13 ± 40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.36 - .78</td>
<td>-2 - 28</td>
</tr>
<tr>
<td>Knee Extensor RFD 95% CI or Q1-Q3</td>
<td>442 ± 199</td>
<td>64 ± 120</td>
<td>9 (42)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19 - 110</td>
<td>-9.6 - 41</td>
</tr>
</tbody>
</table>

![Figure 2. The relationship between maximal voluntary RTD and MVC.](image)
proportion of variance in RTD explained by maximal strength is lower than the 50 – 80% reported by Andersen and Aagard 90 ms after the onset of contraction. Furthermore, Andersen and Aagard report voluntary RFD to be highest at 0-50 ms and descending towards 0-200ms. We report the opposite trend as RTD is ~50% greater at intervals between 0-200ms compared to 0-50ms. These results suggest that RTD in the early stages of muscle contraction is lower than in young adults and also that factors influencing RTD 0-50 ms after the onset of contraction are less related to maximal strength. The lower RTD in the early phase of contraction may be due to age-related changes in the musculotendinous compliance [27], such that a reduction in connective tissue stiffness may require a greater duration of muscle contraction in order to develop appropriate tension for force transmission [28-30].

Maximal muscle strength accounted for ~38% of the variance in maximal RTD. The linear phase of the contraction would appear (Figure 1) to occur between 50-150 ms after the onset of contraction which would be in line with the trend of maximal muscle strength explaining 22-70% of the variance in RTD at time points 0-100 ms and 0-200 ms from the onset of contraction. As RTD was highest when estimated during the linear phase of contraction, we suggest this is the section of the torque-time trace where the rate of cross-bridge formation is greatest. The results further highlight that the method for determining RTD is key to the physiological interpretation. It would appear that RTD cannot be used as a broad based term as is the case with maximum torque derived from an MVC. In line with the age-related difference in peak torque and muscle quality we reported previously [3], RTD was lower for women in the 7th decade of life compared to those in the 6th decade and this difference was greater in the knee extensors. The difference in knee extensor RTD was almost double (-28%) that of knee extensor torque (-15.7%) that we reported previously in the functional tests used and the exercise prescribed would have been detailed in our recently published manuscript. RTD was not altered by 12 weeks of PRT despite improvements in peak torque, muscle quality and extended gait speed which rises completed in 30 seconds. Furthermore, knee extensor RTD was not altered by 12 weeks of PRT despite improvements in peak torque, muscle quality and extended gait speed which have been detailed in our recently published manuscript [16]. The weak association with functional capability and the lack of change due to intervention may be linked to the time interval from which RTD was sampled (~50-150 ms) and the fact that the functional tests used and the exercise prescribed would likely require muscle contractions of >200 ms. The exercises in this intervention were performed to a count of 4 seconds for the eccentric phase and 2 seconds for the concentric phase. As part of the healthy ageing study we reported moderate correlations between knee extensor strength and the extended gait speed and chair rise tests reported in this manuscript [17] As the variance in RTD explained by maximal muscle strength increases with time from the onset of contraction, it is likely that RTD sampled at later time points may have had an association with functional tasks and or been altered due to PRT. The associated increase in upper leg LTM and maximal strength with the PRT in this study may have arisen via an increase in the diameter of type IIA muscle fibre diameter but at the expense of a relative reduction in type IIX fibres characterised by a high RFD [35]. It is also possible that the increase in fascicle length and resultant increase in compliance cancels out the increased shortening velocity of muscle arising from having more sarcosomes in series [29].

We report RTD from the most linear phase of the torque-time trace in the majority of this analysis. The associations reported in this study as well as the age and intervention related differences must be interpreted cognisant of the variability in the measure. A broader consideration for performing this form of analysis is that there is a significant researcher time cost. Exporting isometric contractions and quantifying RTD at different points or from the most linear slope of the time-torque trace is a laborious process. Given that this process produces values of limited reliability, researchers should consider alternate non-invasive measures of quantifying intrinsic muscle contractile properties such as Tensiomyography (TMG), Myotonometry (MMI) [36] and Mechanomyography (MMG) [37].

REFERENCES

25. Tracy BL, Enoka RM. Older adults are less steady during submaximal isometric contractions with the knee extensor muscles. J Appl Physiol 2002; 92 (3):1004-1012.