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Does weightlifting increase residual force enhancement?

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ABSTRACT

The force maintained following stretching of an active muscle exceeds the isometric force at the same muscle length. This residual force enhancement (RFE) is different for various muscles. It is currently unknown whether training induces changes in RFE. Weightlifters perform a large number of eccentric contractions during training, and RFE might be functionally relevant. The aim of this study was to examine whether there is increased RFE in weightlifters versus a reference group.

Therefore, we measured external reaction forces during a multi-joint leg extension in weightlifters ($n=10$) and a reference group ($n=11$) using a motor driven leg press dynamometer (ISOMED 2000). Steady state isometric forces after stretching were compared to the corresponding forces obtained during isometric reference contractions. Statistical analyses yielded a significant RFE for both groups ($p<0.001$), but there were no RFE differences between the groups ($p=0.320$). However, RFE tends to decrease slower in the weightlifting group versus the reference group.

We conclude that long-term weightlifting has only a minor influence on RFE. We speculate that the specific training including a combination of eccentric and concentric exercises induced almost no changes in titin-isoform expression which may be responsible for generation of RFE after active muscle stretching.

1. Introduction

It has been known for more than 60 years that muscle force is enhanced (RFE, residual force enhancement) in the isometric phase following active stretching versus the isometric force at the corresponding muscle length (Abbott and Aubert, 1952). RFE has been detected at the myofibrillar level (Joumaa et al., 2008), in muscle fiber (Edman et al., 1982; Edman and Tsuchiya, 1996), in muscle (Abbott and Aubert, 1952; Siebert et al., 2015), and for multi-joint movements (Hahn et al., 2010). Furthermore, RFE has been observed during maximal (Hahn et al., 2010) and submaximal (Pinniger and Cresswell, 2007; Seiberl et al., 2012) muscle activation.

Muscles differ in the amount of RFE. Using the same experimental setup and conditions, Siebert et al. (2015) found muscle specific differences in 6 different rabbit shank muscles in the range of 8%–30% maximum isometric force (F_{im}). Hahn et al. (2007) observed no significant RFE in human quadriceps femoris muscle during maximum voluntary contraction (MVC). In contrast, RFE was reported to reach up to 25% F_{im} in several single and multi-joint movements (see Seiberl et al., 2015a, for review). For example, the RFE was confirmed for plantar flexion and dorsiflexion in the range of 7%–13% (Hahn et al., 2012; Pinniger and Cresswell, 2007; Tilp et al., 2011). Interestingly, RFE of dorsiflexors increased with age from about 8% in young (about 16 years) to 22% in old (about 76 years) people (Power et al., 2012).

The reasons for the observed differences in residual force enhancement are unclear. Differences may be attributed to different muscle functions and/or training. It is well known that muscles adapt e.g., architecture, fiber-tendon length ratio, and fiber type depending on their function (Biewener, 1998; Mörl et al., 2015; Roberts and Azizi, 2011; Rome et al., 1988). Moreover, among other strength training methods eccentric muscle training evokes gains in muscle strength and size (Hortobagyi et al., 1996; LaStayo et al., 2000). It apparently also results in increasing leg and muscle stiffness in humans trained on a high-force eccentric ergometer for 8 weeks (30 min three times per week) (Lindstedt et al., 2002). Additionally, an eccentrically trained group of basketball players increased their vertical jumping height versus a traditional strength/power resistance-training group. The differences were attributed to the higher leg stiffness and an increased storage and release of elastic energy (Lindstedt et al., 2001). The authors suggested that the protein titin may significantly contribute to the force production when the muscle actively lengthens and that titin

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may function as an adaptable muscle spring (Lindstedt et al., 2001; Lindstedt et al., 2002). In a study with rats, eccentric muscle training increased muscle stiffness during active muscle stretch, but this did not increase the rats' maximum isometric force (Lindstedt et al., 2002). Increased muscle stiffness during stretching may be directly related to RFE (Rode et al., 2009; Till et al., 2010). Therefore, the ability of muscles to produce enhanced muscle stiffness and/or RFE might be a plastic feature of muscles depending on their use (Lindstedt et al., 2002; Rode et al., 2009).

The mechanisms of RFE are a matter of intense scientific debate (Campbell and Campbell, 2011; Edman, 2012; Siebert and Rode, 2014). While some researchers advocate mechanisms based on classic theories of contraction including half-sarcomere inhomogeneities (Morgan et al., 1982) and altered cross-bridge dynamics (Walcott and Herzog, 2008), others relate them to a non-cross-bridge, semi-active contribution of titin to muscle force (Leonard and Herzog, 2010; Lindstedt et al., 2002; Nishikawa et al., 2012; Rode et al., 2009; Till et al., 2010). Indeed, titin-actin interactions seem to be a serious candidate to explain RFE (Herzog et al., 2015; Siebert and Rode, 2014).

There are a series of studies examining the impact of training and exercise on titin isoform expression. Titin content was reduced due to direct damage or degradation of titin following a single high-intensity eccentric resistance exercise of human *M. vastus lateralis* (Trappe et al., 2002). However, Lehti et al. (2009) reported no change in titin mRNA expression 2 days after fatiguing jumping exercise. Examination of muscle adaptation after training periods (8–15 weeks) including stretch-shortening exercises and explosive jump squat training resulted in no changes in titin isoforms (Kyrolainen et al., 2005; McGuigan et al., 2003). Interestingly, McBride at al. (2003) observed differential expression of titin isoforms in weight- and powerlifters in comparison to untrained non-athletic individuals. This might be an indication for training induced changes in RFE of weightlifters. However, none of the training or weightlifting studies focusing on changes in titin expression examined the influence of training on RFE.

Weightlifters perform many submaximal eccentric contractions in their training (e.g. squats with barbell loaded with 1.5–2.5 bodyweight). The relevance of RFE for stretch-shortening cycles of the human *M. adductor pollicis* was recently reported (Seiberl et al., 2015b) and RFE might be relevant in storing and releasing energy during squats, too. Furthermore, submaximal eccentric contractions might be sufficient to trigger RFE mechanisms, since RFE was observed for submaximal eccentric contractions (Pinniger and Cresswell, 2007; Seiberl et al., 2012). Therefore, we hypothesize that weightlifters exhibit RFE, and that the amount of RFE is higher than that of a reference group. To investigate this hypothesis we determined the RFE during maximal voluntary multi-joint leg extensions in a weightlifter and in a reference group, respectively, using a motor driven leg press dynamometer.

2. Methods

2.1. Subjects

We enrolled 21 subjects with no history of ankle, knee, or hip joint injury or neurological disorders. Free, written informed consent was obtained from all subjects and the study was conducted according to the latest Declaration of Helsinki. The weightlifter group ($n=10$, age: 26 ± 5 years, weight: 94 ± 18 kg, height: 178 ± 5 cm) practiced weightlifting competitively (7 subjects in the highest German national league and 3 subjects in the Thuringia regional league). They trained on average 4 times per week for 2 h. Typical training exercises are the deadlift, squats with the barbell on the thorax (front squat) or nape (back squat), snatch, as well as clean and jerk. The reference group consisted of sport students ($n=11$, age: 27 ± 4 years, weight: 81 ± 9 kg, height: 182 ± 6 cm) with no experience in weighlifting but with experience in sports (e.g., volleyball, basketball, swimming, tennis, or gymnastics).

Fig. 1. Experimental setup. The subject is placed in the motor-driven leg press dynamometer (IsoMed 2000).

2.2. Force and length measurements

Unilateral leg extensions were performed with the preferred kicking leg using a motor-driven leg press dynamometer (IsoMed 2000, D&R Ferstl GmbH, Germany). Unilateral leg extension (Fig. 1) was selected as a test movement as this multi-joint movement shows similarities to squats performed regularly during weightlift training. Force (perpendicular to the force plate) and length data were recorded with a sampling frequency of 200 Hz (MP150, Biopac Systems, Goleta, USA) and stored on a computer. Subjects were placed on the dynamometer with a back rest inclined 30° from an upright position and a foot position 0.1 m above the dynamometer seat. The footrest was individually adjusted between 10° and 15° from upright position towards plantarflexion to enable whole foot contact during knee extension. Force was measured during pure isometric contractions at 110° and 90° knee angles where 180° corresponds to a full leg extension. The dynamometer leg press length positions at 180°, 110°, and 90° knee joint angle were defined as lengths $L_{180}=0$ cm, L_{110}, and L_{90}, respectively. These were determined for each subject individually. Furthermore, isometric-eccentric-isometric stretch-contractions were performed from 110° to 90° resulting in a 20° range of motion in the knee joint similar to Seiberl et al. (2013). This contraction is named the stretch-contraction throughout the remainder of the manuscript. In the stretch-contraction, the dynamometer footrest was moved linearly from L_{110} to L_{90} with a velocity of 30 cm/s. Depending on the individual leg length proportions of the subjects, this movement leads to a mean knee angular velocity of $52°/s\pm11°/s$, which is slightly lower than 60°/s used by Hahn et al. (2010) and Seiberl et al. (2012). Subject specific differences in angular velocity are expected to have no influence on RFE because RFE is independent of stretch velocity (Edman et al., 1978; Siebert et al., 2015).

2.3. Test protocol

Participants performed a warm-up consisting of rope skipping (200 jumps) and 20 squats. They were then placed in the leg press dynamometer (Fig. 1) and the pelvis and upper body were secured using safety belts and shoulder pads. During the test, the participants conducted maximum voluntary contractions (MVC). They were instructed to increase their leg extension forces to the maximum level and to maintain the force for 4 s. Meanwhile, the participants were constantly encouraged by vocal instruction (Donath et al., 2014). The test started with three maximum voluntary isometric contractions at 110°. The maximum force was used to define a 90% trigger ($F_{90\%\_110}$) for the stretch-contractions. The participants then conducted three maximum voluntary isometric contractions at 90°. Following these pure isometric contractions, the participants performed three stretch-contractions. The stretch started (t_{start}) after the participants reached $F_{90\%\_110}$ in the first isometric part (Fig. 2). Contractions were maintained for 3 s following stretching (t_{end}) to ensure a steady-state force in the second isometric part following the stretch-transient force response. Rest between the experiments was 3 min, which was sufficient to avoid fatigue.

2.4. Data analysis

Forces were smoothed with a second order Butterworth low pass filter with a cutoff frequency of 20 Hz. The mean force-time traces of the three isometric contractions at 90° as well as for the three stretch-contractions were calculated (Fig. 2) and used for further analyses. Due to restrictions of the ISOMED2000 software, force measurement during stretch-contraction started at t_{start} ($F_{90\%\_110}$) at the beginning of the eccentric ramp. For a better understanding, we present a draft of the initial force trace of the first isometric phase in Fig. 2 (black broken line).