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Effect of concentric and eccentric velocity during heavy-load non-ballistic elbow flexion resistance exercise

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Abstract

Objectives: The current study provided a longitudinal evaluation of the anthropometric and fitness characteristics in junior rugby league players across three annual-age categories (i.e., under 13s, 14s and 15s) considering playing position and selection level.

Design: Longitudinal design.

Methods: Eighty-one junior rugby league players selected to a talent development programme were tracked over a two year period. Anthropometric (height, sitting height, body mass and sum of four skinfolds) and fitness (lower and upper body power, speed, change of direction speed and maximal aerobic power) characteristics were measured on three occasions (i.e., under 13s, 14s and 15s). Repeated measures multivariate analysis of variance (MANOVA) and multivariate analysis of covariance (MANCOVA; controlling chronological and maturational age) analysed changes across annual-age categories in relation to playing position and selection level.

Results: Findings identified significant improvements in anthropometric and fitness characteristics across annual-age categories ($p < 0.001$). MANOVA and MANCOVA analysis identified significant overall effects for playing position ($p < 0.001$) and selection level ($p < 0.05$) throughout the two year period. Interactions between playing position and time were identified for height, vertical jump and estimated VO^sub 2max^ ($p < 0.05$). Selection level by time interactions were identified for 20 m, 30 m and 60 m sprint ($p < 0.05$). Conclusions: This study demonstrates the improvement of anthropometric and fitness characteristics within junior representative rugby league players. Interactive effects for playing position and selection level by time highlight the variation in the development of characteristics that occur during adolescence. Tracking the progression of characteristics longitudinally during adolescence, instead of at one-off time points, may assist selection and/or performance assessments within rugby league and other youth sport contexts.

Keywords

effect, concentric, eccentric, velocity, during, heavy, load, non, ballistic, exercise, flexion, elbow, resistance

Disciplines

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***Title page (including all author details and affiliations)**

EFFECT OF CONCENTRIC AND ECCENTRIC VELOCITY DURING HEAVY-LOAD NON-BALLISTIC ELBOW FLEXION RESISTANCE EXERCISE

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Abstract

Objectives: Mechanical and neuromuscular benefits arise during ballistic stretch-shortening cycle muscle activation, yet resistance training regimens are typically non-ballistic, and in contrast to ballistic movement, require a concentric deceleration phase. Design: Twelve healthy males performed a unilateral, six repetition maximum non-ballistic elbow flexion-extension task during; i) rapid shortening (**RS**), ii) stretch-shortening cycle (**SSC**) and iii) a 2-second eccentric and 2-second concentric control (**C**). Method: A load cell and shaft encoder recorded respectively force and velocity. Surface electromyographic root mean square amplitude (EMG_{RMS}) was recorded in the *biceps* and *triceps brachii*, and are reported as the relative (%) difference, normalised to control (**C**). Results: The average lengthening and shortening velocity of **SSC** (0.57 ±0.03m·s^{-1}; 0.43 ±0.02m·s^{-1}) was significantly greater than **RS** (0.22 ±0.01m·s^{-1}; 0.35 ±0.01m·s^{-1}), and **C** (0.17 ±0.00m·s^{-1}, 0.20 ±0.00 m·s^{-1}). Peak eccentric force was increased (P<0.0001) and in the first 5% of concentric movement during **SSC**, in the first and last repetitions respectively (194.7 ±8.4 N, 164.1 ±7.5 N) when compared to **RS** (163.3 ±8.9 N, 152.4 ±7.5 N) and **C** (155.9 ±8.5 N, 152.2 ±8.7 N). Eccentric EMG_{RMS} in the *biceps brachii* was significantly increased during the first three and final repetitions of **SSC** (31.9 ±10.9%, 46.7 ±12.4, 69.3 ±13.6%, 92.0 ±16.4%), and the third and last repetitions of **RS** (35.9 ±7.4%, 50.3 ±10.9%), compared to **C** (0.00%, 15.8 ±4.0%, 23.7 ±4.1%, 39.2 ±8.6%). Conclusion: In the current study, eccentric limb velocity potentiated eccentric and concentric force, concentric velocity, and eccentric EMG amplitude during non-ballistic exercise.

KEYWORDS: Stretch-shortening cycle, force, velocity, resistance exercise, electromyography

Introduction

Running, jumping and throwing actions are typical ballistic stretch-shortening cycle activations, characterised by acceleration throughout the entire range of motion, leading to limb projection, or release of an object into free space [1].These ballistic muscle activations are consistently associated with increased skeletal muscle work, power and mechanical efficiency [2-4]. However, despite these mechanical advantages, non-ballistic muscle activation is commonly prescribed within heavy-load resistance training regimens [5, 6]. Thus, within this investigation we intended to determine if the mechanical advantages associated with ballistic muscle activations could be obtained during heavy-load non-ballistic movement.

Relatively light load, non-ballistic muscle activation coupled with an eccentric countermovement significantly elevates force and power output [7, 8]. However, it is well established that a relatively heavy training mass is fundamental to the development of force within the neuromuscular system [2, 9, 10]. For example, loads greater than 80% of a single repetition maximum (1 RM) are most readily observed to elicit muscle hypertrophy, neural adaptation and strength gain [11, 12]. Thus, within this investigation we were interested in determining the effect of rapid non-ballistic muscle activation using loads equal to 85% of 1RM, an area that has received little attention. Newton et al. observed increased electromyographic activity as the external load increased during ballistic upper-limb stretch-shortening cycle activations [2]. The authors proposed that the prolonged contraction times and slower velocities associated with the increasing load allowed for a greater proportion of the motor unit pool to be activated.

In each of these investigations an eccentric countermovement condition was compared to a concentric only condition [2, 7, 8]. The mechanical advantage gained from stretch-shortening muscle activation is improved during ballistic activities when the velocity of the eccentric countermovement is increased [3, 13, 14]. It is therefore not known if heavy-load non-ballistic resistance exercise displays any of the mechanical or neuromuscular attributes typically observed during ballistic stretch shortening muscle activation. Currently, the literature has only examined the effect of stretch-shortening muscle activation during heavy-load resistance exercise on a single repetition [2, 7, 8]. However, resistance exercise regimens commonly involve multiple repetitions, performed to volitional failure. Uniquely, this investigation therefore examined the effect of heavy-load, upper-limb non-ballistic stretch-shortening resistance exercise performed to repetition failure, by quantifying the effect of limb movement velocity on force output and electromyographic responses.

Methods

Twelve healthy, active male participants with recreational resistance exercise experience (26 SD 3.9 y, 180.5 SD 7.9 cm, and 79.1 SD 11.9 kg) participated in the current experiment after providing written, informed consent and a medical history questionnaire. All procedures were approved by the Human Ethics Research Committee at the University of Wollongong. Participants visited the laboratory on three separate occasions, a minimum of 48 h apart.

On each visit participants were positioned supine with the hips and knees flexed at 90°. The forearm was supinated, and the participant was connected to an external load via a steel cable and leather wrist strap (Figure 1). Kinetic, kinematic and electromyographic responses were recorded during three experimental movement conditions involving dominant limb elbow flexion and extension, commencing at 60° and terminating at 160° of flexion; i) a control (**C**) performed slow (2 s) flexion and (2 s) extension, ii) rapid shortening (**RS**) performed maximal acceleration during flexion and a slow (2 s) extension, and iii) stretch shortening cycle (**SSC**) performed maximal acceleration during flexion and extension. During each condition, participants were provided with continuous visual and auditory feedback (Labview Ver.8.0, National Instruments Corporation, Austin, U.S.A). No specific instructions were given in regards to transition from eccentric to concentric movement. Each participant performed the three conditions and therefore acted as their own controls.

The single joint exercise (Figure 1) was chosen to maximise the experimental control of movement, and isolate the elbow flexors by restricting lumbar extension and auxiliary muscle activation.

INSERT FIGURE 1 ABOUT HERE

Each participant visited the laboratory on three separate occasions, first to determine the maximum mass participants could successfully complete six repetitions through the desired range of motion (6RM), secondly, to confirm 6RM, and become familiar with the three movement conditions, and finally to assess kinetic, kinematic and electromyographic (EMG) data during the three conditions using the pre-determined 6RM. On this third visit, each of the three conditions were performed randomly in separate blocks. To facilitate movement processing, a shaft encoder (E6C2-CWZ6C-1000, Omron, Minato-ku, Tokyo, Japan) with a resolution of ~0.07 mm was mounted onto the experimental equipment, acting as the first pulley wheel, whilst providing distance, time and direction data during muscular contractions (Figure 1). The shaft encoder data were recorded at 2000 Hz via an analogue to digital converter (Power 1401, Cambridge Electronic Design, Cambridge, U.K.) instrumented in series within the Digitimer (Neurolog Hertfordshire, U.K.) recording device. Force (N) was recorded simultaneously via a 1000 N load cell (Applied Measurement, X-TRAN, 51W-1kN, Eastwood, Australia) connected in series with the resistance equipment (Figure 1), instrumented by a DC voltage amplifier, sampling at 200 Hz (Neurolog, 108A, Digitimer Neurolog, Hertfordshire, U.K.).

Prior to the first block of movements, the arm of each participant was passively moved through the 160-60° range of motion, providing an individual displacement calibration from the shaft encoder. Using the pre-determined 6RM load, participants performed one set of elbow flexion and extension exercise to volitional repetition failure in each of the three conditions (randomised), separated by 30-min rest. Total time under tension (s) and total displacement (Δpulse n × 0.07 mm, compared to the calibration reading) were calculated from the first shaft encoder pulse during the first eccentric repetition, to the last pulse of the last successful concentric repetition prior to repetition failure [15]. Total work (J), was calculated as the product of mass (m = 6RM load, kg), acceleration (a = 9.81 $m \cdot s^{-2}$) and displacement (d = Δpulse n × 0.07). Average velocity ($m \cdot s^{-1}$), during shortening and lengthening (Δdistance/time), and the delay between lengthening and shortening, (last eccentric pulse, to the first concentric pulse) from the first, second, third and last successfully completed repetition were further analysed. In addition, velocity ($m \cdot s^{-1}$) and force (N) were calculated at 5% intervals relative to total displacement during the first and last repetition.

To assess the fatigue induced by, and subsequent recovery from each condition, a 5-s maximal voluntary, isometric contraction (MVC) was performed at 120° of elbow flexion prior to commencing each condition and, immediately following volitional repetition failure. Participants were given verbal encouragement, with visual feedback of force generation provided via an oscilloscope.

Surface electrodes (Ag/AgCL, contact diameter 15 mm) were adhered to the *biceps* and *triceps brachii* with a 2 cm inter-electrode distance, positioned over the centre of each muscle belly, parallel to the orientation of muscle fibres, midway between the elbow crease and acromion process. A reference electrode was adhered to the central portion of the clavicle. Electromyographic signals were pre-amplified with a low frequency cut off to 3 Hz, amplified 1000 times and high- and low-band pass filtered via the Power 1401 analogue to digital converter and digitmer recording device (10-500 Hz, Neurolog 844, 820, 144, 135, Digitimer Neurolog, Hertfordshire, U.K). Data were collected at 2000 Hz per channel, and analysed using Spike 2 software (Ver 5.13, Cambridge Electronic Design, Cambridge, UK). Average EMG root mean square (EMG_{RMS}), calculated during shortening and lengthening phases of the first, second, third and last repetition are reported as the relative (%) difference, normalised to the first eccentric or concentric control (**C**) repetition. The change in EMG_{RMS} from first to last repetition was normalised within conditions.

Statistical analyses were performed using a Multivariate Analysis of Variance (*MANOVA*), with condition as the independent variable. If significant effects were observed, a One-Way repeated measures (*ANOVA)* was used followed by a *post-hoc* Tukey's HSD correction for multiple comparisons. Data are reported as means and standard errors of the mean (±), unless otherwise stated as standard deviation (SD). Statistical significance was set at an *alpha* level of <0.05.

Results

No significant difference was observed in the number of repetitions performed, or total work (J) prior to volitional repetition failure in **SSC** (7.5 ±2.2, 751.7 ±69.8 J), **RS** (6.0 ±2.0, 576.3 ±62.4 J) and **C** (6.0 ±2.0, 550.7±67.7 J) conditions. Total time under tension was however reduced by over 40% and 30% respectively (*P*=0.0009) during **SSC** (14.4 ±1.7 s) and **RS** (17.1 ±1.6 s) compared to **C** (25.3 ±2.9 s).

The average velocity of lengthening and shortening was higher (*P*<0.0001) in the first three **SSC** repetitions (0.57 ±0.03 $m{\cdot}s^{-1}$, 0.43 ±0.02 $m{\cdot}s^{-1}$) when compared to **RS** (0.22 ±0.01 $m{\cdot}s^{-1}$, 0.35 ±0.01 $m{\cdot}s^{-1}$) and **C** (0.17 ±0.00 $m{\cdot}s^{-1}$, 0.20 ±0.00 $m{\cdot}s^{-1}$). However, analysis of the first repetition indicates that the elevated shortening velocity was only apparent in the first 15% of limb displacement when compared to **RS** (Figure 2b). Muscle shortening velocity decreased with each subsequent repetition in all conditions, and by the last repetition (Figure 2d), no significant difference was observed between **SSC** (0.25 ±0.02 $m{\cdot}s^{-1}$) and **RS** (0.22 ±0.16 $m{\cdot}s^{-1}$), yet each remained (*P*<0.0001) greater than **C** (0.14 ±0.01 $m{\cdot}s^{-1}$).

INSERT FIGURE 2 ABOUT HERE

Compared to **C**, the epoch between lengthening and shortening during **SSC** was reduced during repetitions one (0.019 ±0.002 s and 0.008 ±0.000 s, *P*<0.0001), two (0.018 ±0.003 s and 0.009 ±0.000 s, *P*=0.0397) and three (0.018 ±0.001 s and 0.011 s, *P*<0.0001). Compared to **RS**, however significance was only observed in the first repetition (0.014 ±0.000 s and 0.008 ±0.000 s, *P*<0.0001). In the third repetition this epoch was also reduced during **RS** compared to **C** (0.012 ±0.001 and 0.018 ±0.001 s *P*<0.0001).

Force displacement curves for the first and last repetitions are illustrated in Figure 3. In the first repetition, peak force was increased (*P*<0.0001) during **SSC** eccentric and concentric (209.8 ±10.8 N, 194.7 ±8.4 N) phases of contraction when compared to **RS** (131.2 ±8.0 N, 163.3 ±8.9 N) and **C** (124.3

±9.1 N, 155.9 ±8.5 N). Peak force in all conditions occurred during the final 5% of eccentric and initial 5% of concentric movement. At the onset of eccentric movement force was lower (*P*=0.0023) during **SSC** (81.1 ±9.2 N) when compared to **RS** (104.7 ±6.2 N) and **C** (103.1 ±6.9 N) and, in the first repetition, remained significantly lower (*P*<0.05) for the first 50% and 45% of eccentric movement when compared to **RS** and **C**. However, a significant increase (*P*<0.05) in eccentric force was observed in the last 30% (70-100%) of **SSC**. Similar to the first repetition, eccentric force during the last repetition of **SSC** was depressed (*P*<0.0001) for the first 25%, and elevated in the final 30% of movement (*P*<0.05) when compared to **RS** and **C**. During the first 5% of concentric movement **SSC** force (164.1 ±7.5 N) was increased (*P*<0.0001) when compared to **RS** (152.4 ±7.5 N) and **C** (152.2 ±8.7 N) and a sharp fall in force output was observed in the last concentric repetition in all conditions.

INSERT FIGURE 3 ABOUT HERE

Peak MVC force prior to each experimental condition was similar between **SSC** (424.2 ±19.1 N) **RS** (403.6 ±16.3 N) and **C** (427 ±26.2 N) indicating participants were well rested prior to commencing each of the three conditions. Immediately following volitional repetition failure, peak MVC force declined (**SSC** 17.4 ±2.0%; **RS** 16.8 ±1.4%; and **C** 16.1 ±1.3%; *P*<0.0001). No significant difference were observed between conditions, suggesting similar levels of muscular fatigue existed across conditions [16].

Concentric and Eccentric EMG_{RMS} values observed during the three exercise conditions are shown in Table 1. Significant differences in eccentric EMG_{RMS} activity were observed between conditions. In repetitions one (*P*=0.0147) and two (*P*=0.0139) *biceps brachii* EMG_{RMS} was increased during the eccentric phase of **SSC** (31.9 ±10.9%, 46.7 ±12.4) in comparison to **C** (0.00%, 15.8 ±4.0%) and in the third (*P*=0.0027) and last (*P*=0.0025) repetitions of **SSC** (69.3 ±13.6%, 92.0 ±16.4%) in comparison to **C** (23.7 ±4.1%, 39.2 ±8.6%) and **RS** (35.9 ±7.4%, 50.3 ±10.9%). No significant differences were observed in *triceps brachii* EMG_{RMS} between conditions.

INSERT TABLE 1 ABOUT HERE

Over time (first to last repetitions), a significant increase in *biceps brachii* EMG_{RMS} during eccentric (P<0.0001) and concentric (P<0.0001) phases was observed during **SSC** (60.1 ±16.4%, 48.2 ±16.1%), **RS** (44.5 ±10.9%, 28.2 ±13.3%) and **C** (39.2 ±8.6%, 31.0 ±7.2%). An increase (P<0.0001) in concentric *triceps brachii* EMG_{RMS} activity was only observed in **C** (24.0 ±5.4%) and no change in eccentric *triceps brachii* EMG_{RMS} was observed in any condition. A decrease in cable tension may have influenced the EMG data, however, peak eccentric acceleration during **SSC** was recorded as 8.8 $m \cdot s^{-2}$ ±0.7, (less than gravity), suggesting the cable maintained tension during eccentric movement.

Discussion

This investigation examined the neuro-mechanical responses of muscle during a simple single joint, heavy-load, non-ballistic resistance activity. Uniquely, the effect of a rapid eccentric countermovement was examined, and shown to increase concentric movement velocity, force and electromyographic activity in the agonist muscle. These observations may suggest that heavy load resistance exercise may benefit from rapid eccentric and concentric muscle activation. However this mode of resistance exercise has to our knowledge not been formally assessed.

The most marked changes were observed during the eccentric phase, where **SSC** eccentric limb velocities were ~4-5-fold higher than **RS** and **C** in the first repetition A rapid pre-stretch preceding muscle shortening enhances concentric velocity in ballistic stretch-shortening cycle activations [2, 17, 18]. However, the present investigation novelly quantified the impact of eccentric contraction velocity during heavy load, upper limb non-ballistic resistance exercise. An increase in the velocity of eccentric muscle activation during non-ballistic activity significantly elevated force production toward the completion of the eccentric phase. Increased eccentric force generation appears to directly facilitate the onset of concentric activation during ballistic stretch-shortening muscle activation [4]. Similarly, despite conditions of relatively heavy external loading and non-ballistic muscle activation in this study, concentric force generation was also enhanced during the first 45 ms of **SSC**, and is likely to have caused the elevation in concentric movement velocity observed within the first 135 ms. This elevation in **SSC** shortening velocity is also similar to the potentiating influence observed during typical, ballistic stretch shortening activities [8, 19].

In the present investigation, participants were not required to produce maximal displacement velocities during **C**, or during the eccentric phase of **RS**, rather movement occurred to a fixed 2-s cadence, as such the time delay observed between the end of eccentric and onset of concentric movement was reduced during **SSC**. Minimising the delay between lengthening and shortening, may directly assist the transfer of force, potentiate shortening velocity and increase the economy of muscular work ballistic stretch shortening muscle activation [3, 8, 20]. However, some caution should be applied to interpretation of this phase of the movement, as it is known that muscle fibre length does not always directly correlate with a change in joint angle [21].

Due to the nature of non-ballistic movement, deceleration at the end of the elbow flexion resulted in a significant decline in force in both **SSC** and **RS**, such that no difference in average force production was observed during muscle shortening between all three conditions. In contrast, ballistic stretch-shortening cycle activations do not demand any concentric deceleration, and velocity and force have been shown to remain elevated throughout the duration of movement [2].

In the current investigation, the relative load was equivalent, and the average force generated during muscle lengthening was similar across conditions. However, during **SSC** exercise, the final 40% of eccentric movement required almost twice as much force to decrease the velocity of lengthening compared to **RS** and **C**. The increased force output is likely explained by the braking demand associated with high velocity eccentric contractions, it is thus likely that contractile mechanisms enhanced force potentiation during the elevated active state of muscle during preload [4, 22, 23]. Consistent with this notion, a significant increase in *biceps brachii* EMG_{RMS} was observed during eccentric muscle activation in the **SSC** condition. However, EMG_{RMS} during concentric muscle activation was similar across all repetitions **SSC**, **RS** and **C.** This investigation has therefore uniquely shown that rapid muscle lengthening preceding muscle shortening during heavy-load non-ballistic resistance exercise, facilitates eccentric rather than concentric muscle activation, a finding consistent with ballistic stretch-shortening cycle muscle activation [23, 24].

A novel element of the current investigation was the completion of repetitions to failure, a common element of heavy-load resistance exercise programs [5, 6]. In this investigation, repetition failure caused a decline and leftward displacement in eccentric force and velocity thus, active eccentric deceleration during **SSC** was occurring earlier in the movement when approaching repetition failure. This prolonged period of deceleration with fatigue permits sufficient time to generate the necessary braking force required to control limb range of motion, and is a characteristic observed in ballistic stretch-shortening cycle activities [25, 26]. Unexpectedly, in the **RS** condition we observed a significant increase in eccentric velocity at repetition failure, suggesting that participants had lost some control in maintaining the required pace of the lengthening movement. We wondered if participants were attempting to increase eccentric velocity in order to take advantage of enhanced force potentiation for the concentric phase [3, 24]. In concentric muscle activation, the velocity displacement curve for all three conditions at repetition failure, was characterised by an initial elevation in velocity followed by a decline, and then second elevation in velocity. Such a response is consistent with a sticking point in the movement [27].

Practical implications

- Similar to ballistic stretch shortening muscle activation, eccentric and concentric peak force, concentric velocity, and EMG activity were affected by the velocity of eccentric movement during heavy-load non-ballistic resistance exercise.
- These findings are of interest as it is known that increased tensile loading, particularly during muscle lengthening, is a potent stimulus for skeletal muscle adaptation.
- However, as volitional repetition failure approached concentric force potentiation was diminished, suggesting task failure may be less important than traditionally prescribed.

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Table 1: Mean EMG_{RMS} (mv) ±SEM observed in the biceps and triceps during eccentic (**ECC**) and concentric (**CON**) phases of the first three, and last repetitions of the control (**C**), rapid shortening (**RS**) and stretch-shortening cycle (**SSC**) exercise conditions.

	Repetition / contraction phase							
Group / muscle	**1**		**2**		**3**		**Last**	
	ECC	**CON**	**ECC**	**CON**	**ECC**	**CON**	**ECC**	**CON**
C-$_{biceps}$	0.33 ±0.03	0.61 ±0.06	0.37 ±0.03	0.68 ±0.06	0.40 ±0.03	0.75 ±0.07	0.45 ±0.03	0.79 ±0.07
C-$_{triceps}$	0.04 ±0.01	0.05 ±0.01	0.04 ±0.01	0.05 ±0.01	0.04 ±0.01	0.06 ±0.01	0.04 ±0.01	0.06 ±0.01
RS-$_{biceps}$	0.34 ±0.03	0.55 ±0.04	0.39 ±0.03	0.58 ±0.05	0.43 ±0.04	0.64 ±0.05	0.48 ±0.04	0.70 ±0.06
RS-$_{triceps}$	0.04 ±0.01	0.06 ±0.01	0.04 ±0.01	0.06 ±0.01	0.05 ±0.01	0.06 ±0.01	0.05 ±0.01	0.06 ±0.01
SSC-$_{biceps}$	0.43 ±0.04	0.53 ±0.04	0.46 ±0.04	0.60 ±0.05	0.54 ±0.05	0.62 ±0.06	0.61 ±0.07	0.81 ±0.08
SSC-$_{triceps}$	0.06 ±0.01	0.07 ±0.01	0.07 ±0.01	0.06 ±0.01	0.06 ±0.01	0.07 ±0.01	0.06 ±0.02	0.07 ±0.02

Figure legends

Fig 1 Set-up demonstrating the experimental position. Dominant limb elbow flexion was performed through a 100° range of motion, with end points marked by via guide bars positioned at 60°-160° of flexion. Computer guided feedback was provided to assist participants in controlling both the range of motion and velocity of movement during controlled (2 s) phases of movement. A light provided a visual stimulus for the onset and termination of a maximal voluntary isometric contraction

Fig 2 Velocity displacement curves during the eccentric phase of the first repetition (A), the concentric phase of the first repetition (B), the eccentric phase of the last repetition (C) and the concentric phase of the last repetition (D), during stretch-shortening cycle (SSC), rapid shortening (RS) and control (C) conditions. Data represent means ± SEM

Fig 3 Force displacement curves during the eccentric phase of the first repetition (A), the concentric phase of the first repetition (B), the eccentric phase of the last repetition (C) and the concentric phase of the last repetition (D), for stretch-shortening cycle (SSC), rapid shortening (RS) and control (C) conditions. Data represent means ± SEM

Figure 1
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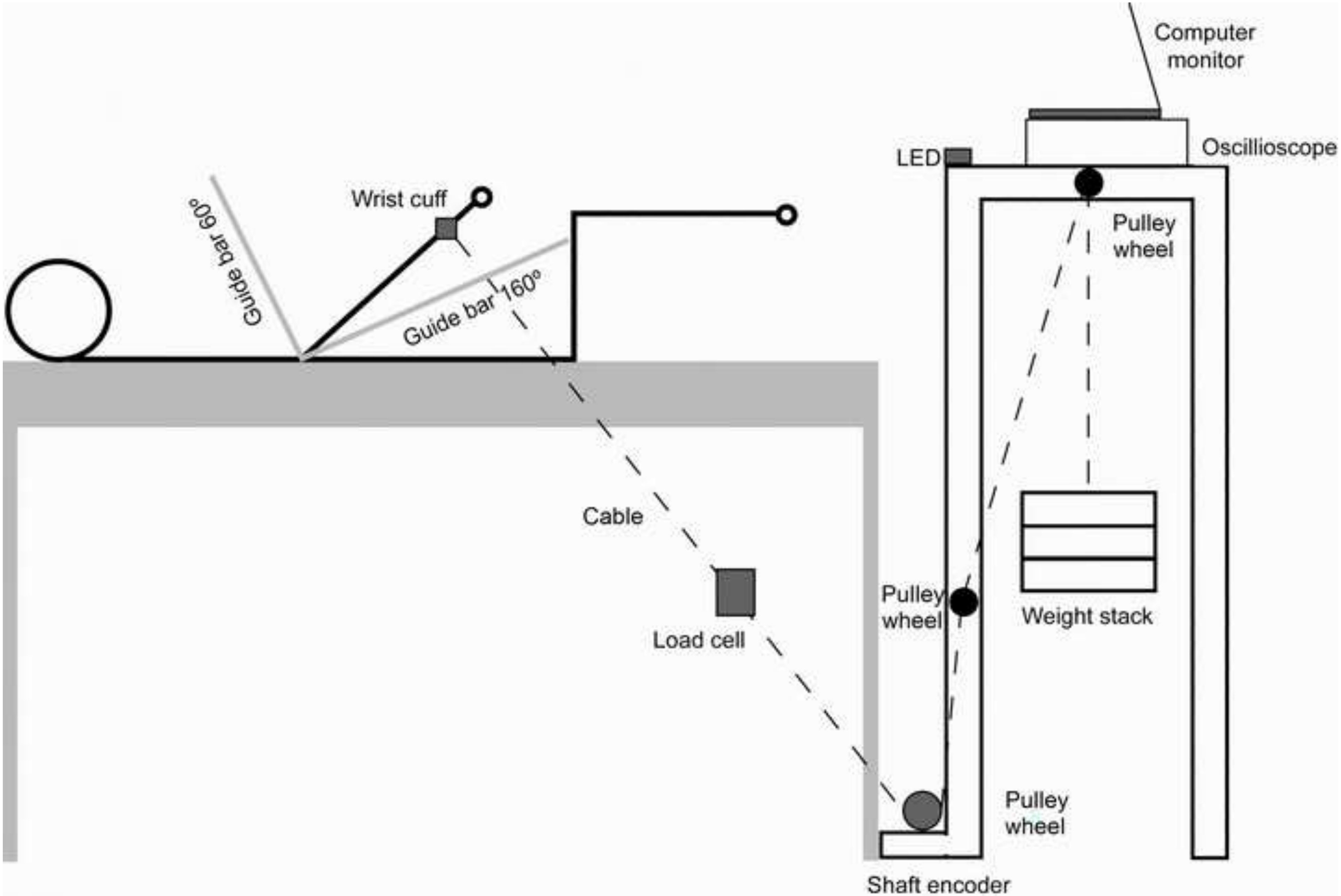

Figure 2

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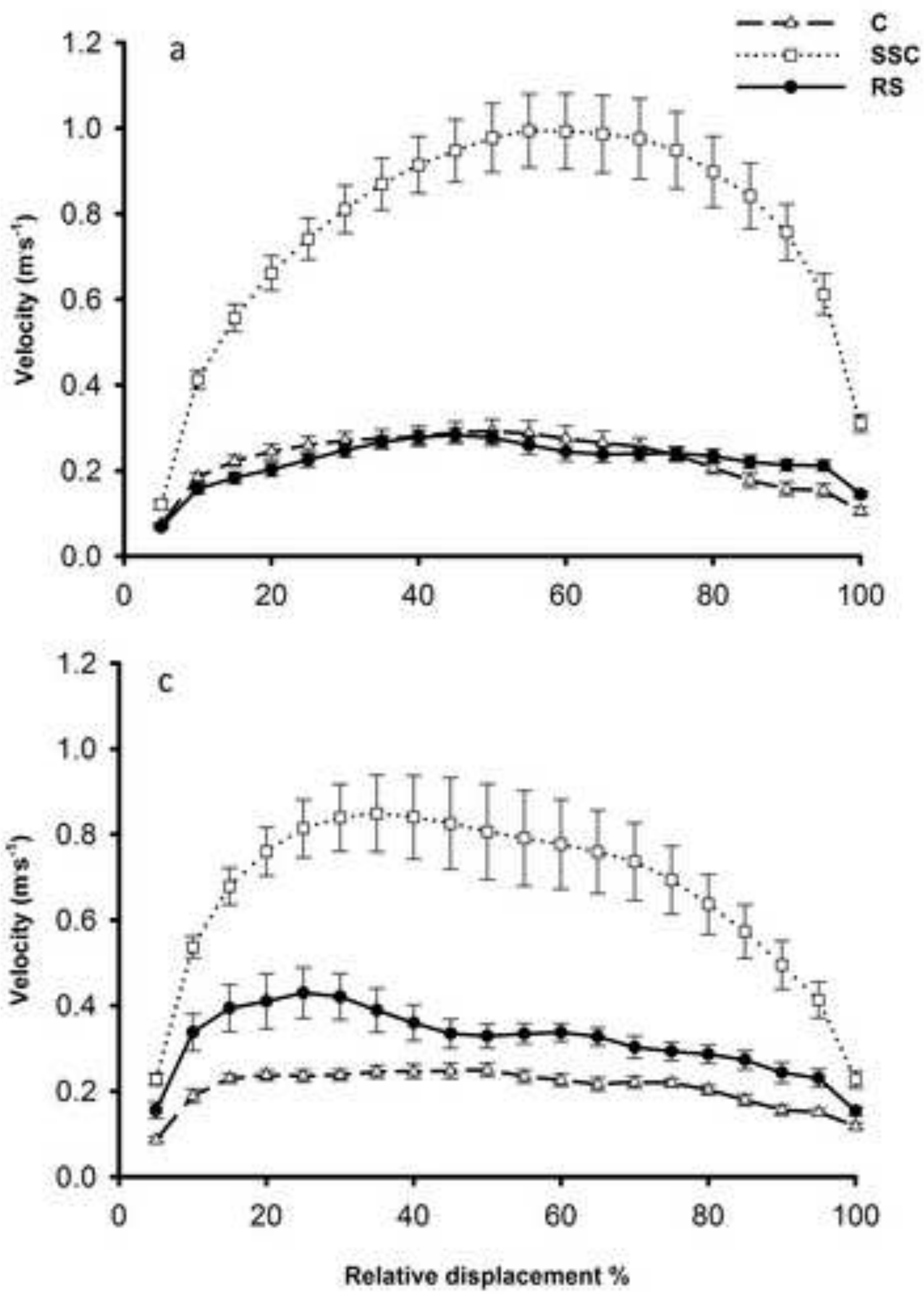

Figure 3
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