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ORIGINAL ARTICLE

Does cheating pay: the role of externally supplied momentum on muscular force in resistance exercise

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Abstract Our work investigates the use of "external momentum" in the context of hypertrophy-oriented training. This is momentum supplied to the load (such as a dumbbell) used in an exercise by means of action of muscles not inherently involved in the exercise. We challenge the general consensus that the use of such momentum often described as "cheating" is counterproductive. We focus on the use of external momentum in the shoulder lateral raise and adopt a framework whereby exercise execution is simulated on a computer. This is achieved using a physical model of motion which is combined with anthropomorphic measurements and empirical data of muscular recruitment from previous work. The introduction of moderate momentum (producing initial angular velocities around 57.5° s^{-1}) increases the torque of the target muscles even without an increase in the load used. A moderate increase in the load and the use of momentum allows the torque to be increased even further. In contrast, excessive use of momentum results in lower demands on the target muscles, while an excessive increase of the load reduces the total hypertrophy stimulus by virtue of the decreased number of repetitions which can be performed successfully and thus the dramatically shortened time under tension. Our results disprove the conventional belief that the use of external momentum necessarily reduces the overload of the target muscles. A moderate use of external momentum increases both the per-repetition peak torque and the total hypertrophy stimulus in a set.

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Introduction

The momentum of a moving object is a physical quantity intimately linked to the object's kinetic energy and the force that needs to be applied over time to bring the object to rest. In performance-oriented sports, the ability to develop momentum by means of rapid force production is a highly desirable capability. For e.g. the momentum of the shot put at the time it is released by the athlete had in part been supplied to it by a direct action of the athlete's muscles and in part transferred to it from the momentum of the athlete's spinning body (Costa et al. 2000). In sprinting, the momentum of the sprinter is developed by the reactive force from the ground, equal in magnitude to the force exerted by the sprinter against the ground (Jaric and Markovic 2009). Considering the role that momentum plays in these sports it is no surprise that its importance is also reflected in the resistance training practices of the athletes. This involves the choice of loads which are sufficiently heavy to demand high force output but not so heavy to compromise the athlete's ability to accelerate it rapidly.

Momentum is an important factor in resistance training itself too, and can greatly affect the amount of load that can be lifted successfully and the effort required to do so. In a compound exercise such as the squat which involves a coordinated action of several functionally separate muscle groups, the momentum generated following the full squat position can be used to overcome the subsequent biomechanical weakness at the mid-point of the concentric part of the lift. A similar technique can be used in the bench press

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to overcome the weakness exhibited when a significant contribution to the effective force exerted against the load is transferred from the pectoral muscles to the anterior deltoid (Padulo et al. 2012; Arandjelović 2011). In weightlifting, momentum is even more important. Both in the snatch and in the clean and jerk, it is essential to supply sufficient momentum to the barbell during the pulling phase to ensure that it reaches the height at which it can be caught by the lifter (Zatsiorsky 1995).

The benefits of explosive execution of exercises in resistance training for performance-oriented sports are readily evident both from theory and empirical study (Winwood et al. 2011). In contrast, the role of momentum in training practices of individuals whose goal is not performance per se but rather hypertrophy is far less clear. As we will discuss in detail in "Momentum in resistance exercise", a change in the momentum of the load affects both the force demands for the successful completion of the lift as well as the environment in which the said muscular force needs to be produced. Some of these changes have the effect of reducing the effective load experienced by the target muscles, others of increasing it. The magnitude of the relative contributions of these effects and the factors which influence them have not been examined thoroughly in the literature.

The aim of this work is specifically to examine a particularly controversial training practice of using "external momentum" and analyze its effects in the context of hypertrophy-oriented training. We use the term "external momentum" to designate any momentum supplied to the load used in an exercise by means of action of muscles not inherently involved in the exercise. This concept is discussed in additional detail in "Momentum in resistance exercise".

The remainder of this paper is organized as follows. In "Momentum in resistance exercise" we review the key physics background pertaining to the concept of momentum and discuss it in the context of resistance training. The relevant mechanics of the shoulder lateral raise, which is the exercise we focus our study on, is the topic of "Shoulder lateral raise: its mechanics and form". "Experimental methodology" summarizes the experimental methodology adopted in the present paper. Experimental results are presented and discussed in "Results and discussion". Finally, the key contributions of our work and its main findings are summarized in "Conclusions".

Momentum in resistance exercise

The linear momentum of an object of mass m moving with the velocity $\mathbf{v}$ is:

$$\mathbf{p} = m\mathbf{v}, \tag{1}$$

or, for a system of n objects of masses $m_1, \ldots, m_n$ and the corresponding velocities $\mathbf{v}_1, \ldots, \mathbf{v}_n$:

$$\mathbf{p} = \sum_{i=1}^{n} m_i \mathbf{v}_i. \tag{2}$$

Note that just like velocity, the momentum is a vector. The analogous angular formula for rotational motion is:

$$\mathbf{L} = \sum_{i=1}^{n} I_i \omega_i. \tag{3}$$

where $\mathbf{L}$ is the angular momentum about a given centre of rotation, and $I_1, \ldots, I_n$ and $\omega_1, \ldots, \omega_n$ the corresponding moments of inertia (units of m kg) and angular velocities (units of s^{-1}).

The momentum of a moving body is intimately linked to the force that needs to be applied to change its velocity. Specifically, the relationship emerges from Newton's second law and is given by:

$$\mathbf{F} = \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t}. \tag{4}$$

Importantly, the momentum (both linear and angular) is a conserved quantity. This means that the total momentum of a system which is not acted upon by external forces remains constant even though the momenta of individual bodies within the system can change.

This relationship readily provides insight into the importance of momentum in resistance exercise. The greater the momentum of the load lifted, such as that of a weighted bar or a dumbbell, the longer the load will sustain motion against gravity even in the absence of any additional force exerted against it by the trainee. As a corollary, the momentum may be used to overcome biomechanically weak points in a lift. Indeed, this phenomenon is often exploited by strength and power athletes such as powerlifters and weightlifters (Swinton et al. 2009). In the bench press, the powerlifter may benefit from the momentum developed early in the lift which helps overcome the biomechanical weakness exhibited as the brunt of the experienced resistance moves from the pectoral muscles to the anterior deltoid, and then the triceps brachii. The importance of momentum is even more pronounced in weightlifting. Both in the snatch, and the clean and jerk, the development of sufficient momentum in the early stages of the lift is crucial for the successful completion of the lift (Cormie et al. 2011; Hardee et al. 2012).

While it can be said that the development of the momentum of the load is desirable in performance sports in which the goal is to maximize the amount of weight successfully lifted, the role of momentum in hypertrophy-oriented training is far less clear. Indeed, no previous research has attempted to investigate this systematically. In the consideration of the impact of momentum on hypertrophy-oriented training, it is useful to distinguish between two different manners in which momentum can be supplied to the load. Firstly, the momentum can be developed by increasing the force exerted by the prime movers in the earlier stages in the lift. In this scenario, it is still the target muscles which are performing all the work required to complete the lift but with a different distribution of work across the range of motion. This practice is not the main interest of the present work. The second scenario involves the use of "external momentum", i.e. momentum supplied by the action of muscles not inherently involved in the exercise performed. The use of external momentum is most commonly associated with isolation exercises, which are generally performed with lighter absolute loads. For e.g. initial momentum at the bottom most point of the one arm shoulder lateral raise exercise can be supplied to the dumbbell using a lateral swing of the torso; similarly in the standing barbell curl exercise the momentum at the bottom most point can be supplied using a forward swing of the torso. This practice is nearly universally considered counterproductive (Hay et al. 1983; Johnston 2005; Fisher et al. 2011). Indeed, this is readily apparent by noting that in the common vernacular the term used to describe it is "cheating" which is inherently associated with negative connotations.

The principal argument against the use of external momentum in exercise is that it reduces the force applied on the target muscles. When analyzed in more detail, the reduction in muscular force can be seen to emerge from two sources. Firstly, less force needs to be exerted against the load which already has some kinetic energy. Secondly, the ability of the target muscles to produce force is hyperbolically reduced as the speed of contraction is increased (Hill 1953). For an isolated muscle this relationship is given by the well-known Hill's equation:

$$F(v) = F_{\max} \frac{v_{\max} - v}{v + K} \frac{K}{v_{\max}} \quad (5)$$

where v is the speed of contraction, $F_{\max}$ the maximal voluntary force for $v = 0$, and $v_{\max}$ the speed of contraction at which the muscle's potential for generating force vanishes.

While the aforestated argument certainly raises valid points, by itself it does not lead to a conclusive answer regarding the usefulness or lack thereof of external momentum in applying force on the target muscles. The key reason is to be found in the observation that the use of external momentum may facilitate the use of greater loads. If the momentum is supplied to the load at a point in the lift at which the target muscles are in a biomechanically inferior position to exert effective force, this weakness may be overcome allowing greater force to be applied in the range of motion which is better suited for overloading the target muscles. For e.g., at the beginning of the shoulder lateral raise (0° humerothoracic elevation), the line of pull of the deltoid muscle is significantly worse than in the middle of the range of motion (30–60° humerothoracic elevation).

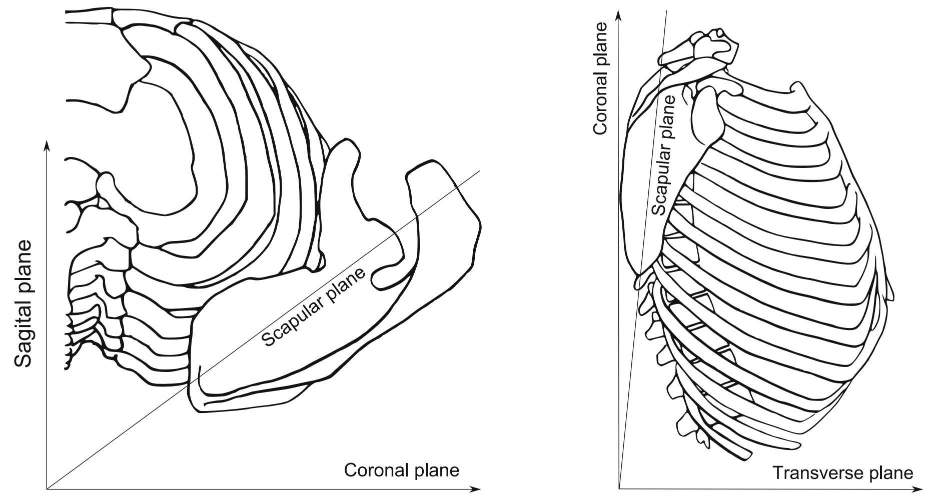
Since the use of external momentum has both desirable and undesirable consequences, qualitative analysis is insufficient and a quantitative method is needed instead. Clearly, the details of such a quantitative method are specific to a particular exercise and its biomechanics. In the present work, we specifically focus our attention on the shoulder lateral raise performed with a heavy dumbbell. Consequently, all numerical outcomes of our experiments should be considered specific to this exercise. However, as we will discuss in "Results and discussion", qualitatively interpreted our findings also provide a broad insight into the effects of externally supplied momentum, thus providing the practitioner with a set of general guidelines on when and how this momentum should be used for best results.

Shoulder lateral raise: its mechanics and form

The lateral raise is a popular exercise used to strengthen the musculature of the shoulder. It is often employed for rehabilitation (Andersen et al. 2008), general strength and conditioning (Souza et al. 2011), and hypertrophy (Volek et al. 1999). Traditionally, the exercise is performed with a dumbbell held in each hand although different means of imposing resistance are also possible, for e.g. using pulley-based machines or elastic bands. The upright row exercise can also be considered a variant of the lateral raise in which the motions of the upper limbs are mutually constrained (McAllister et al. 2012). In this paper we focus our attention on the free-weight dumbbell version of the lateral raise.

The principal action taking place during the lateral rise is that of humerothoracic elevation which is performed with a rigid and nearly fully extended elbow. This action is facilitated by glenohumeral and scapulothoracic motions whose instantaneous relative contributions are a function of the elevation angle (Inman et al. 1944). As with any resistance exercise, in the prescription of the correct form two important aspects should be considered. These are the safety of a particular variation on the execution of the exercise, and its effectiveness in subjecting the target muscles to force. In the specific case of the lateral raise, the nature of the performed motion leaves room for the adjustment of (1) the plane of humerothoracic elevation and (2) the degree of glenohumeral joint rotation.

Fig. 1 The scapular plane at rest, shown projected onto the **a** transverse and **b** sagital planes. The change in the position and orientation of the scapula with humerothoracic elevation, and in particular its increasing tilt in the posterior direction, should be taken into account in the consideration of the most effective and safe form for the free-weight lateral raise



(a) Transverse plane projection **(b)** Sagital plane projection

The deltoid and the supraspinatus muscles are the main contributors to the abduction of the upper limb. The involvement of biceps brachii is smaller in magnitude: it vanishes when the humerus is fully medially rotated and increases to its maximal value for full lateral rotation of the humerus. The infraspinatus, teres minor and subscapularis are also activated substantially, stabilizing the glenohumeral joint.

The brunt of the external load resisting humerothoracic elevation is transferred to the deltoid muscle, which comprises three functionally separate groups of fibres: anterior, lateral and posterior. The anterior fibres originate from the anterior border of the lateral third of the clavicle, the lateral fibres from the superior surface of the acromion, and the posterior fibres from the inferior lip of the posterior of the scapular spine. During the abduction of the upper limb the anterior and posterior fibres are mainly recruited in the stabilizing role, their forces being matched by virtue of their opposing actions (Wright 1962). The involvement of the anterior fibres is increased with the increasing angle between the coronal plane and that of the humerothoracic elevation. Interestingly, both the anterior and posterior fibres can act as either adducting or abducting agents, as their lines of pull change orientation relative to the instantaneous centre of rotation (de Luca and Forrest 1973).

Evidence points to the recommendation that both in terms of safety (or conversely, risk of injury) and effectiveness, the lateral raise should be performed with humerothoracic elevation in the scapular plane. This plane is usually 30–40° anterior to the coronal plane (McFarland 2006), as shown in Fig. 1a. This manner of execution results in the closest alignment of the mechanical axes of the humerus and the scapula (Poppen and Walker 1976), provides the best line of pull for the deltoid and the supraspinatus muscles (Johnston 1937) and puts the least amount of stress on the shoulder capsule (Greenfield 1994; Dines and Levinson 1995). In addition, the torso should be slightly forward leaning to account for the increasing posterior tilt of the scapula which occurs during abduction (Poppen and Walker 1976). The initial scapular tilt at rest is approximately 6–9 % in the anterior direction (Sobush et al. 1996; Escamilla et al. 2009), as illustrated in Fig. 1b. By leaning forward, the maximal alignment of the scapular plane and the plane of abduction is attained at the end of the motion, i.e. at roughly 90° of humerothoracic elevation, when the moment of the external load is the greatest.

Experimental methodology

A methodological analysis of the effects of externally supplied momentum on the variation of force experienced by the target muscles in an exercise is prohibitively challenging to implement in an empirical setup. One of the key reasons lies in the difficulty of controlling the amount of momentum supplied, particularly when multiple repetition sets are performed. Instead, in this paper we adopt a mathematical model of exercise execution which allows us to systematically control variables of interest and unambiguously measure and associate the observed effect.

In accordance with our analysis of the biomechanics of the lateral raise in "Shoulder lateral raise: its mechanics and form", we assume that humerothoracic elevation is constrained to the scapular plane. We also assume that the humerus is neither medially nor laterally rotated but rather in the "neutral" position so that the line connecting the medial and lateral epicondyles is always in the plane of humerothoracic elevation, i.e. in our case also coplanar with the scapula. The elbow is nearly fully extended and remains rigid throughout the motion. Thus, the motion performed has one degree of freedom which is the angle of humerothoracic elevation in the scapular plane. If this angle at time t is $\theta(t)$, the motion can be described by the following differential equation:

$$(I_a + I_l) \cdot \ddot{\theta}(t) = T_m(t) - m_a \cdot g \cdot l_c \cdot \sin\theta(t) - m_l \cdot g \cdot l_a \cdot \sin\theta(t) \quad (6)$$

where I_a and I_l are the moments of inertia of the upper limb and the load around the centre of rotation, m_a and l_c respectively the mass and the distance of the centre of gravity of the upper limb from the shoulder's centre of rotation, $T_m(t)$ the net abducting muscular torque at the shoulder, m_l and l_a respectively the mass of the point load and its distance from the centre of rotation, and g acceleration due to gravity as illustrated in Fig. 2. The initial conditions at $t = 0$ are:

$$\theta(t) = 0 \quad (7)$$

$$\dot{\theta}(t) = \begin{cases} 0 : \text{no externally supplied momentum load at rest} \\ \omega : \text{initial angular velocity due to externally supplied momentum} \end{cases} \quad (8)$$

To facilitate a computer-based simulation, Eq. (6) was approximated using the finite differences method. Discretizing time to intervals of duration Δt, the motion was described by the following equations:

$$\ddot{\theta}(k\Delta t) = \frac{T_m(k\Delta t) - m_a \cdot g \cdot l_c \cdot \sin\theta(k\Delta t) - m_l \cdot g \cdot l_a \cdot \sin\theta(k\Delta t)}{I_a + I_l} \quad (9)$$

$$\dot{\theta}(k\Delta t) = \dot{\theta}((k-1)\Delta t) + \Delta t \cdot \frac{\ddot{\theta}(k\Delta t) + \ddot{\theta}((k-1)\Delta t)}{2} \quad (10)$$

$$\theta(k\Delta t) = \theta((k-1)\Delta t) + \Delta t \cdot \frac{\dot{\theta}(k\Delta t) + \dot{\theta}((k-1)\Delta t)}{2} \quad (11)$$

The net abducting torque $T_{\{m\}}(t)$ that can be exerted against the upper limb is dependent on the angle of humerothoracic elevation. This variation is a consequence of the change in the length of the abducting muscles as well as their effective lines of pull. The torque is reduced from its peak both at the beginning and at the end of the range of motion (0 and 90° of humerothoracic elevation, respectively). The peak torque is typically observed at approximately 50° of humerothoracic elevation (Bergmann et al. 2011). This characteristic is shown in Fig. 3. The net abducting muscular torque is further modulated by the angular speed of abduction and the accumulated muscle fatigue. Note that Hill's equation cannot be applied directly in this case, as it only hold true for the contractions of an isolated muscle. Instead we adopt the empirically measured functional form of the relationship between torque and angular velocity from Gore (2000), which is shown in Fig. 4. Lastly, we assume that the trainee is always attempting to exert maximal force against the load and thus adopt a decaying exponential model of fatigue modulation of the form $\exp(-t/\tau)$ (Arandjelović 2010). We estimate the value of the fatigue time constant as $\tau = 60$ s based on the results reported by Minning et al. (2007). In summary, the muscular torque as a function of time can be written as:

$$T_m(t) = T_m^* \cdot f_a(\theta(t)) \cdot f_v(\dot{\theta}(t)) \cdot f_f(t) \quad (12)$$

where T_m^* is the *maximum maximorum* of the torque, and $f_a(\theta), f_v(\dot{\theta}(t))$ and $f_{\{f\}}(t)$ respectively the elevation, angular velocity and fatigue-modulating functions.

The values of the anthropometric variables of the model were chosen in accordance with their averages in adult men scaled to a 100 kg trainee, and are summarized in Table 1. The mass of the upper limb was taken to be 5 % of the total body mass, distributed across the arm and forearm in the ratio of approximately 1.29:1 (Clauser et al. 1969; Smith et al. 1996). The corresponding upper limb, arm and forearm lengths were set to 0.8, 0.446 and 0.354 m, from which the centre of mass of the upper limb was calculated to be at 0.35 m from the centre of rotation during humeral abduction. The values of the moments of inertia of the arm and forearm around their own centres of mass for rotation in the humeral abduction plane were estimated as 0.0268 and 0.0168 kg m^2 respectively (Chandler et al. 1975). The corresponding moments of inertia around the centre of rotation during humeral abduction were computed to be 0.167 and 0.866 kg m^2, using the Huygens–Steiner theorem. This theorem, also known as the parallel axis theorem, states that the moment of inertia I' of a rigid body of mass m about an axis parallel to an axis passing through the body's centre of mass and at distance d from it, can be computed as:

$$I' = I + m \cdot d^2 \quad (13)$$

where I is the object's moment of inertia about the axis passing through the body's centre of mass. Finally, the moment of inertia I_a for the entire upper limb in humeral abduction was calculated by adding the corresponding moments of inertia of the arm and the forearm.

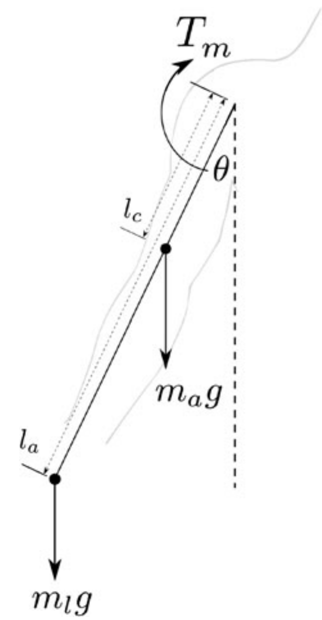


Fig. 2 The key forces and moments involved in scapular plane humeral abduction: I_a is the moment of inertia of the upper limb around the centre of rotation, m_a and l_c, respectively the mass of the limb and the distance of its centre of gravity from the shoulder's centre of rotation, $T_m(t)$ the net abducting muscular torque at the shoulder, and m_l and l_a, respectively the mass of the point load (dumbbell) and its distance from the centre of rotation located between the head of the humerus and the glenoid fossa of the scapula

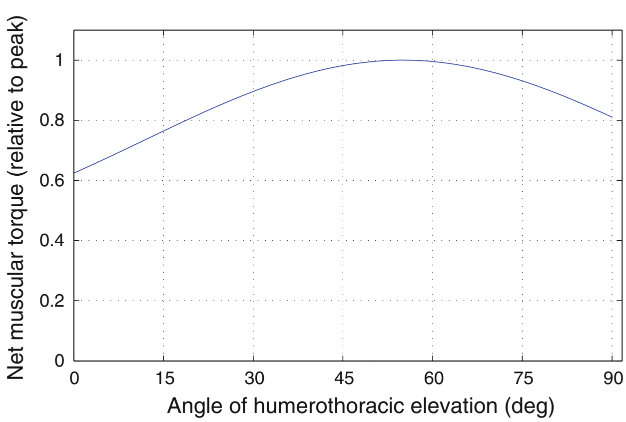


Fig. 3 Empirically measured relationship between the net muscular torque at the shoulder and the angle of humerothoracic elevation

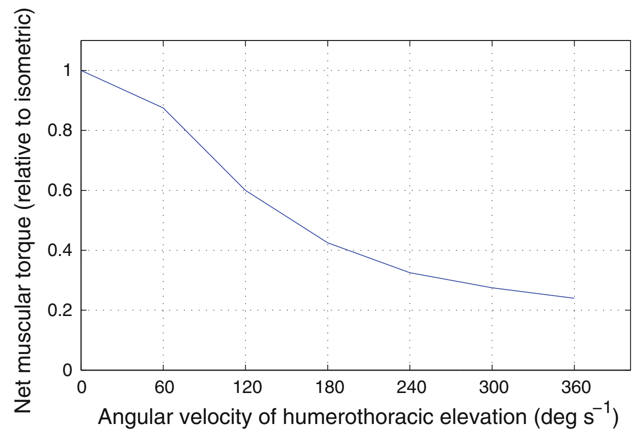


Fig. 4 Empirically measured relationship between the net muscular torque at the shoulder and the angular velocity of humerothoracic elevation (Gore 2000)

Table 1 Values of anthropometric variables used in our experiments

Variable	Value
Maximum maximorum torque (T^*_m)	150 N m
Upper limb mass (m_a)	5 kg
Arm mass	2.815 kg
Forearm mass	2.175 kg
Distance of upper limb centre of gravity from shoulder centre of rotation	0.35 m
Upper limb length (l_a)	0.8 m
Arm length	0.446 m
Forearm length	0.354 m
Arm moment of inertia (about own centre of mass)	0.0268 kg m^2
Forearm moment of inertia (about own centre of mass)	0.0168 kg m^2
Arm moment of inertia (upper limb abduction)	0.167 kg m^2
Forearm moment of inertia (upper limb abduction)	0.866 kg m^2
Upper limb moment of inertia (upper limb abduction; I_a)	1.033 kg m^2

Results and discussion

As the starting point, we performed a simulation experiment using a load (dumbbell) of mass $m_l = 10$ kg. The characteristics of the maximal effort set, which resulted in 10 successful repetitions and a failure on the subsequent one, are summarized in Fig. 5. The plots in Fig. 5a, b show respectively the extent of humeral elevation through time for each repetition and the coupling of the angle and the angular velocity of humeral elevation i.e. the so-called capability plane path of Arandjelović (2010). Considering our choice of the loading, as expected, the first repetition of the set (boldest blue line) is performed with relative ease: following the initial biomechanically challenging position the load is continually accelerated and the repetition is performed with a substantial terminal angular velocity. As the set progresses, the effects of fatigue start to become apparent. The angular velocity reduces for all abduction angles and the final part of the range of motion becomes progressively more difficult. The initially positive angular acceleration at the end of the range of motion first reduces in magnitude and then becomes progressively more negative. The plot in Fig. 5c shows the corresponding variation

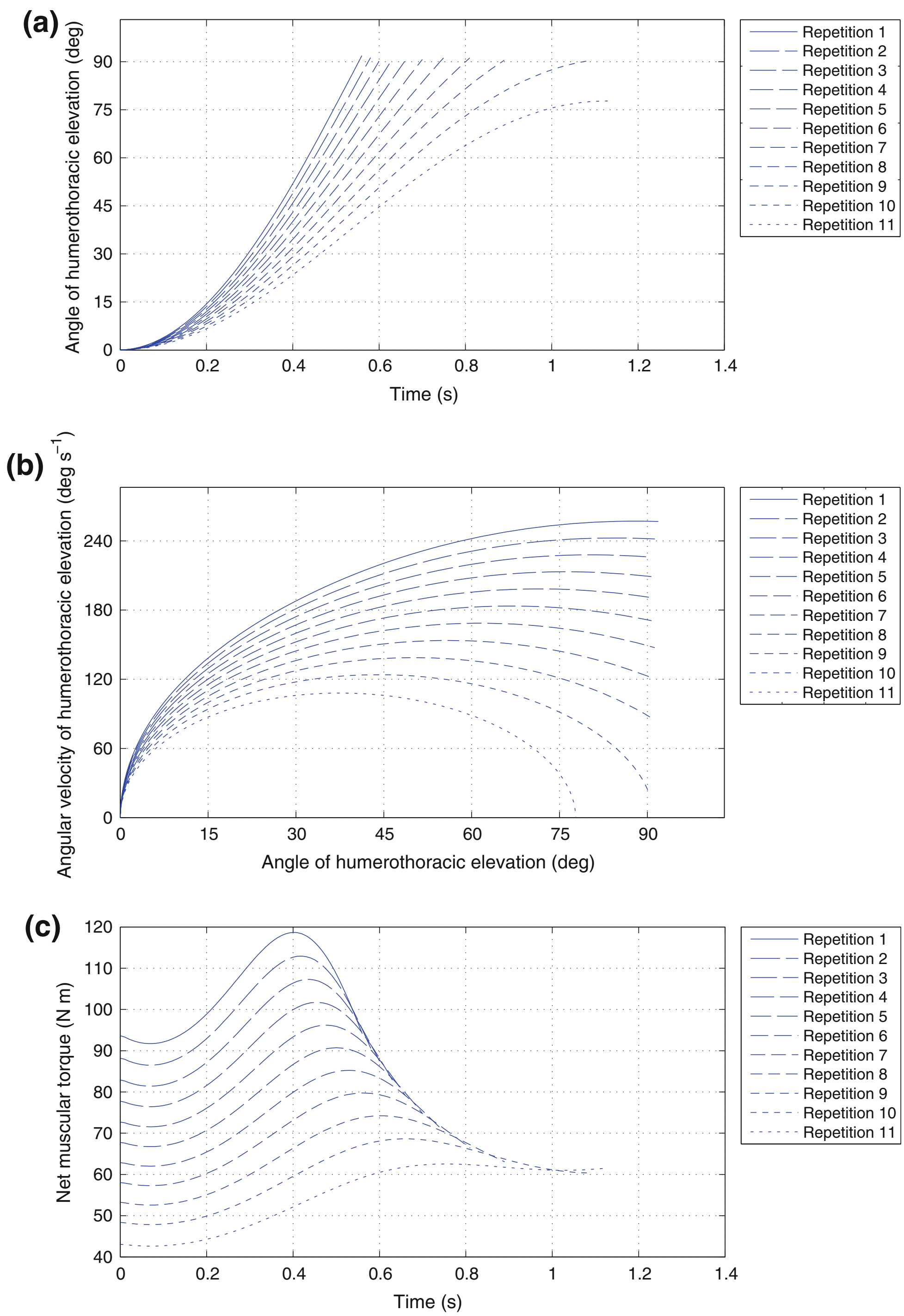


Fig. 5 The characteristics of a set of shoulder lateral raise repetitions performed to failure without the use of external momentum. The trainee successfully performs 10 repetitions and subsequently fails. Notice the decrease in muscular torque at the shoulder and the angular velocity of the dumbbell as the trainee fatigues during the set

in the net torque of abduction exerted by the muscles of the shoulder complex. Interestingly, the torque changes substantially within a repetition. For e.g. in the first repetition the peak torque of approximately 120 N m experienced at humerothoracic elevation of $\theta \approx 57.5°$ is twice the magnitude of the minimal torque experienced at the end of the range of motion (i.e. humerothoracic elevation of $\theta \approx 90°$). It is also insightful to observe that the peak per-repetition torque is consistently experienced at the humerothoracic elevation of approximately 57.5°. The difference effected by the accumulating fatigue is that this angle is reached after an increasing amount of time from the onset of each subsequent repetition which is demonstrated as the shift of the location of the peak in the plot in Fig. 5c.

In the next set of experiments, while keeping the mass of the load (dumbbell) the same we investigated how the introduction of different amounts of externally supplied

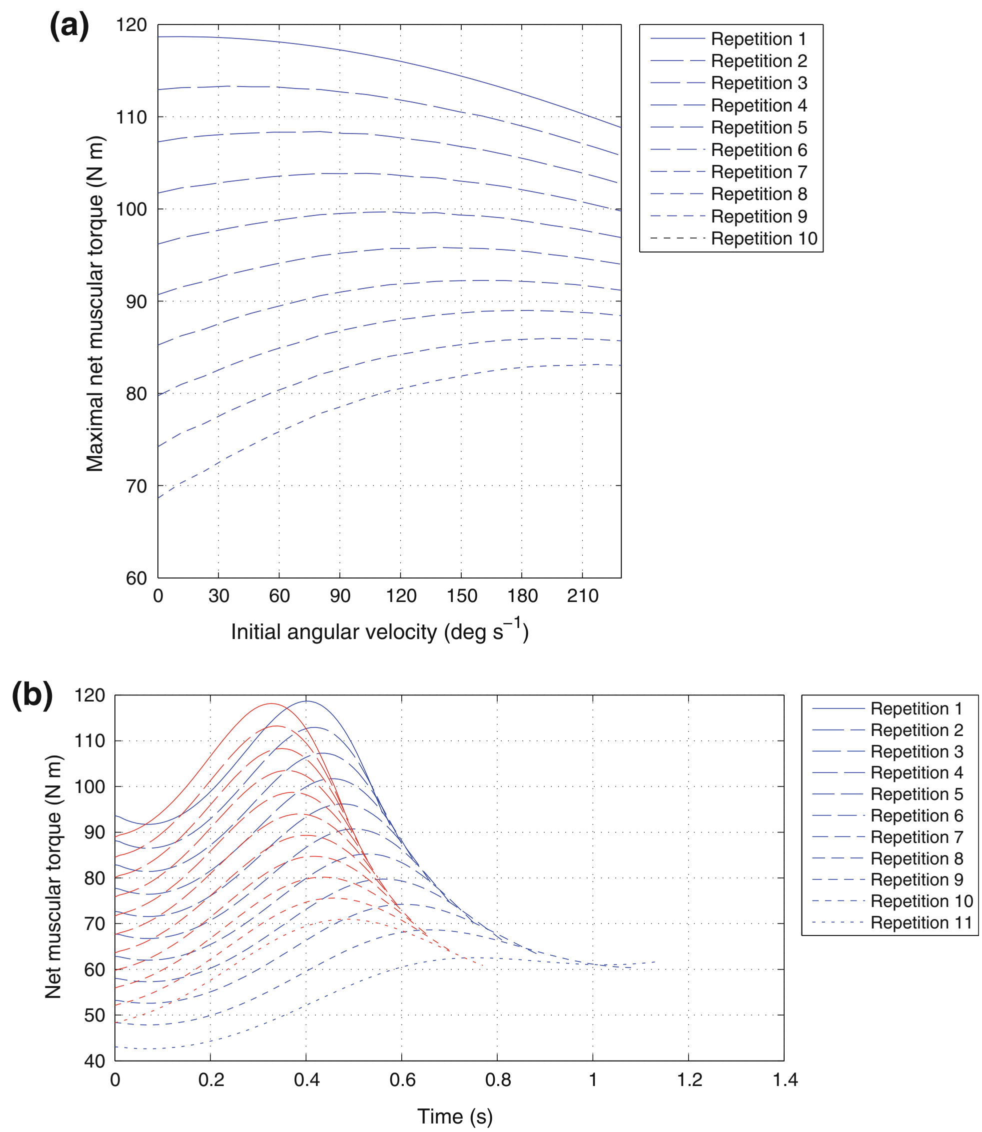


Fig. 6 The change in the loading characteristics of a set of lateral raises experienced for different magnitudes of externally supplied momentum at the beginning of each repetition. Shown are **a** the dependence of the maximal per-repetition torque across the set, and **b** a comparison between the torque characteristics for a set performed without the use of externally supplied momentum (*blue lines*, as in Fig. 5) and with the external momentum at the beginning of each repetition which gives the load the initial angular velocity of 57.5° s^{-1} (*red lines*) (color figure online)

momentum at the beginning of each repetition in a set affects its performance characteristics and the tension experienced by the abducting musculature of the shoulder. The plot in Fig. 6a shows the change in the peak per-repetition muscular torque as the momentum is increased, resulting in initial angular velocities at the beginning of each repetition in the range 0–230° s^{-1}. Notice that the momentum which corresponds to the initial angular velocity of approximately 57.5° s^{-1} produces higher peak forces for all repetitions but the first. This is further illustrated in Fig. 6b which compares the variation in the net torque felt by the muscles of the shoulder without the use of external momentum (blue lines) and for the initial angular velocity of 57.5° s^{-1} (red lines). Not only is there a progressive increase in the per-repetition peak torque differential, but the overall torque experienced is also consistently maintained at a higher level as the set progresses and as fatigue is accumulated.

Next we investigated if properly employed external momentum can be used to overload the muscles even further by facilitating the use of heavier loads (dumbbells). The plot in Fig. 7a compares the per-repetition peak force variation as the momentum is increased for maximal effort sets using 10 kg (blue lines) and 12.5 kg (red lines) dumbbells. The range of initial angular velocities of 57.5–115° s^{-1} again seems to be optimal and when employed with the heavier load produces consistently higher peak muscular torques than those experienced with the lighter load. Notice that as a consequence of the increased load, the number of repetitions which can be completed successfully without any initial momentum is decreased from 10 to 8. As illustrated in Fig. 7a, for the ninth repetition to be completed successfully the initial angular velocity of at least 45° s^{-1} is required. Similarly, the initial angular velocity of at least 70° s^{-1} is needed for the completion of the tenth repetition. In Fig. 7b, a

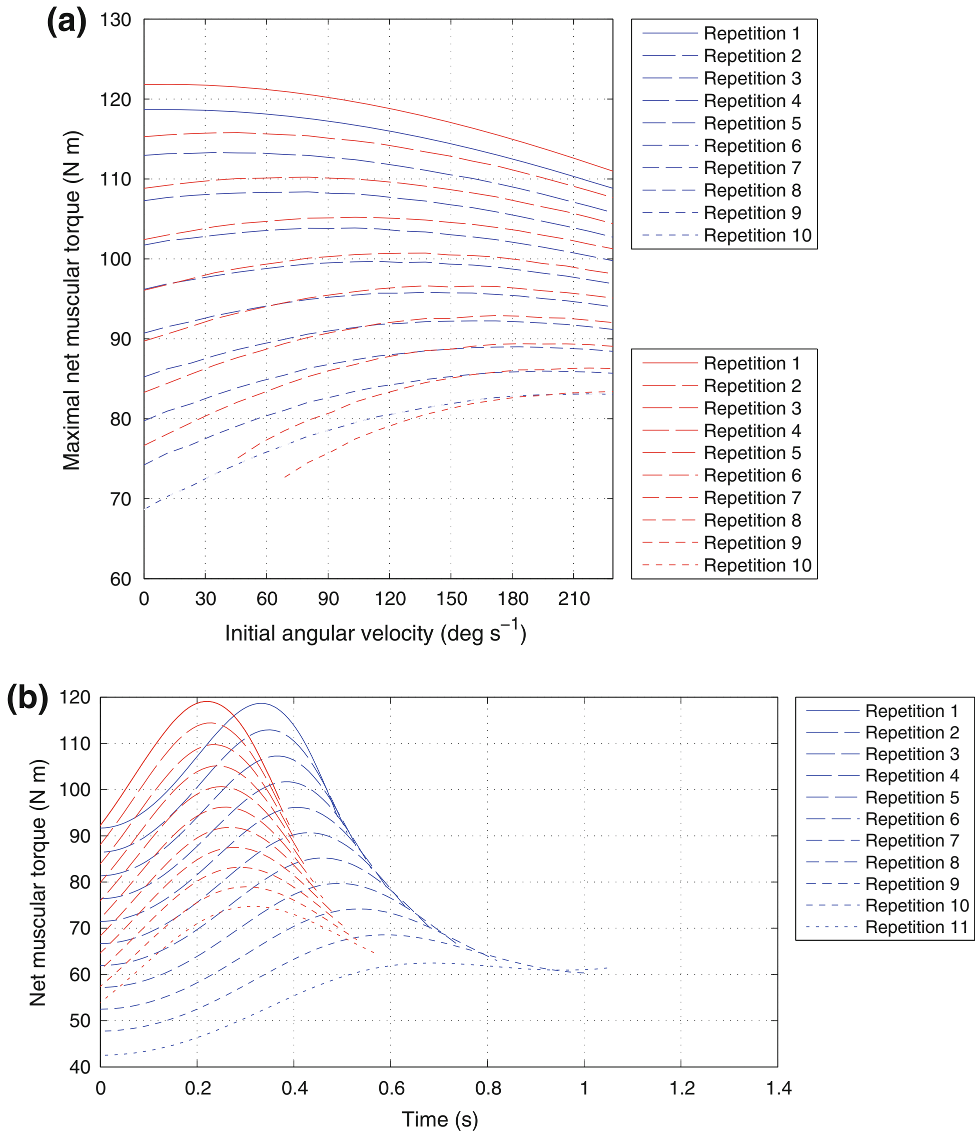


Fig. 7 The change in the loading characteristics of a set of lateral raises experienced for different magnitudes of externally supplied momentum at the beginning of each repetition. Shown are **a** the dependence of the maximal per-repetition torque across the set for $m_l = 10$ kg (*blue lines*) and $m_l = 12.5$ kg (*red lines*), and **b** a comparison between the torque characteristics for a set performed with the load of mass $m_l = 10$ kg and no externally supplied momentum (*blue lines*, as in Fig. 5), and with the load of mass $m_l = 12.5$ kg with external momentum at the beginning of each repetition which gives the load the initial angular velocity of 57.5° s^{-1} (*red lines*) (color figure online)

comparison is made between the loading characteristics achieved in the baseline experiment (10-kg dumbbell, no external momentum) and those when a 12.5-kg dumbbell is used with the initial angular velocity of 57.5° s^{-1}. This figure illustrates the nature of the compromise inherent in the use of externally supplied momentum: while the peak per-repetition torque is increased with the increase in the initial angular velocity, the time under tension for each repetition is reduced.

Even though we have shown that the use of external momentum may be used to increase the peak per-repetition torque, if its value in hypertrophy specific training is the consideration at hand, it is important to also analyze the effects on overall torque variation. As the plot in Fig. 8 demonstrates, the per-repetition minimal torque may be decreased (as witnessed by the increased per-repetition standard deviation of torque for $m_l = 10$ kg); as shown previously, the time under tension may be reduced too. Thus, we were interested in quantifying the change in total amount of hypertrophy stimulus provided by a set as the magnitude of the external momentum supplied at the beginning of each repetition is changed. This stimulus is a function of tension experienced by muscles and the duration of this tension (Babault et al. 2006). It is widely recognized that in conventional resistance training (to distinguish it from resistance training in a highly hypoxic environment, say) there is little hypertrophy stimulus provided below a certain intensity threshold, after which the near maximum stimulation is reached relatively quickly (Campos et al. 2002). We model this phenomenon using a sigmoid function of the form shown in Fig. 9. The total stimulus of a repetition is thus obtained by integrating the net abducting torque, after it is modulated by our sigmoid function. The key results are summarized in Fig. 10.

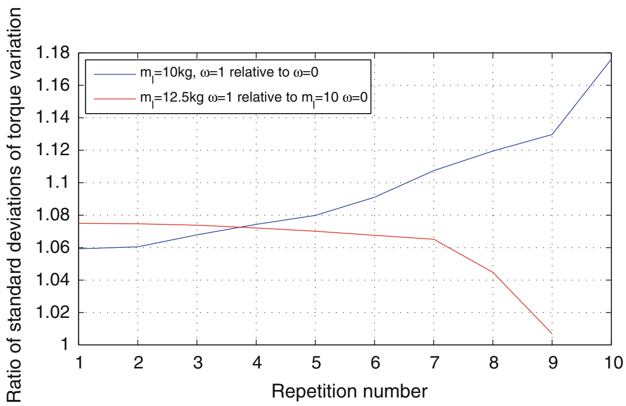


Fig. 8 The variation of the ratio of standard deviations of per-repetition torque relative to the baseline set performed with the load of mass $m_l = 10$ kg and no externally supplied momentum i.e. $\omega = 0° \text{ s}^{-1}$. Shown are the results for $m_l = 10$ kg and $\omega = 57.5° \text{ s}^{-1}$ (*blue line*), and $m_l = 12.5$ kg and $\omega = 57.5° \text{ s}^{-1}$ (*red line*). Notice that in the latter case only nine repetitions are completed successfully (color figure online)

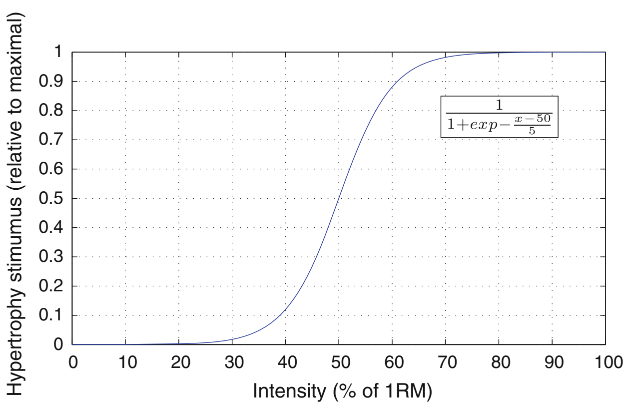


Fig. 9 The sigmoid function used to model the scale of the hypertrophy stimulus as a function of the loading intensity expressed as the percentage of the 1 repetition maximum (1RM)

Initially, as the loading is increased, so does the hypertrophy stimulus for all magnitudes of the external momentum. The same range of initial angular velocities 30–60° s^{-1} which was previously found to maximize the peak per-repetition torque again proves to be the most interesting one, resulting in the highest total stimulus per set. However, when the mass of the load is increased more dramatically, the hypertrophy stimulus drops rapidly for lower initial angular velocities i.e. lower magnitudes of external momentum. The key reason for this is that the number of repetitions which can be successfully completed in a set drops and with it the time under tension. This observation also explains the undulation of the plots which are most noticeable for loads over 12.5/,kg. At discrete intervals, a small increase in the momentum is sufficient to facilitate the completion of another repetition, which results in more time under tension. Lastly, note that high per-set hypertrophy stimulus can be maintained even when

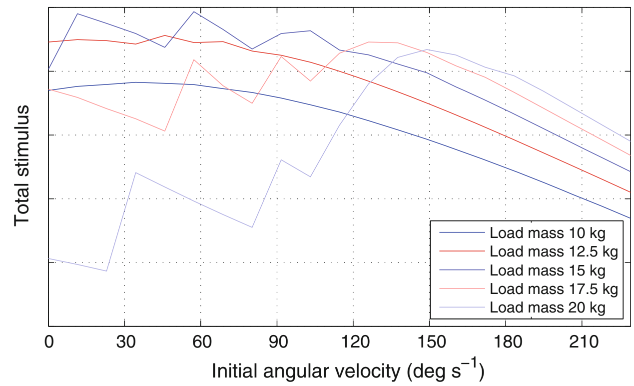


Fig. 10 Relative total hypertrophy stimuli across maximal effort sets performed with different loads (10, 12.5, 15, 17.5 and 20 kg) and using different magnitudes of externally supplied momentum at the beginning of each repetition expressed in terms of initial angular velocity (range 0–230° s^{-1}). When the 10RM load of 10 kg is used, the stimulus is maximized when some momentum is used (resulting in the initial angular velocity of approximately 40–45° s^{-1}). As the load is slightly increased so is the stimulus for all amounts of externally supplied momentum. When the load is increased significantly, the maintenance of the hypertrophy stimulus requires the use of an ever-increasing amount of external momentum but even for its optimal value fails to exceed that of a reasonable increase in the load with a more moderate use of external momentum

the load is greatly increased by accompanying this increase with additional external momentum (e.g. of approximately 145° s^{-1} for $m_l = 20$ kg). However, considering that the resulting stimulus does not exceed that achieved with a more moderate increase in the load and a substantially smaller initial angular velocity (e.g. $m_l = 12.5$ kg and $\omega = 40° \text{ s}^{-1}$), this practice does not appear attractive due to the greater chance of injury and increased overall body fatigue.

In summary, our results suggest that the use of moderate momentum at the beginning of each repetition provides the best compromise between safety, time under tension and the magnitude of tension experienced by the target muscles in the lateral raise. The significant increase in the load that this manner of executing the exercise allows and the greater overload of muscles in biomechanically advantageous positions thus effected, outweigh the negative effects of the associated reduction in the number of repetitions which can be successfully performed and the reduced time under tension.

Conclusions

In this paper we investigated the use of "external momentum" for hypertrophy-specific training. The term external momentum was introduced to describe momentum supplied to the load used in an exercise by means of action of muscles not inherently involved in the exercise. Our work challenged the general consensus that the use of such momentum, often described as "cheating" is counterproductive. In particular, we investigated its use in the context of shoulder lateral raises. Our results suggest that the use of moderate momentum at the beginning of each repetition in a set can facilitate the use of heavier loads and a better overload of muscles in biomechanically advantageous positions. Excessive use of momentum resulted in the lowering of the loading imposed on the target muscles and decreased total hypertrophy stimulus, discouraging its use.

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