

# Stretch-shorten cycle compared with isometric preload: contributions to enhanced muscular performance

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**Walshe, Andrew D., Greg J. Wilson, and Gertjan J. C. Ettema.** Stretch-shorten cycle compared with isometric preload: contributions to enhanced muscular performance. *J. Appl. Physiol.* 84(1): 97–106, 1998.—To isolate any difference muscular contraction history may have on concentric work output, 40 trained male subjects performed three separate isokinetic concentric squats that involved differing contraction histories: 1) a concentric-only (CO) squat, 2) a concentric squat preceded by an isometric preload (IS), and 3) a stretch-shorten cycle (SSC) squat. Over the first 300 ms of the concentric movement, work output for both the SSC and IS conditions was significantly greater ( $154.8 \pm 39.8$  and  $147.9 \pm 34.7$  J, respectively;  $P < 0.001$ ) compared with the CO squat ( $129.7 \pm 34.4$  J). In addition, work output after the SSC test over the first 300 ms was also significantly larger than that for the corresponding period after the IS protocol ( $P < 0.05$ ). There was no difference in normalized, integrated electromyogram among any of the conditions. It was concluded that concentric performance enhancement derived from a preceding stretch of the muscle-tendon complex was largely due to the attainment of a higher active muscle state before the start of the concentric movement. However, it was also hypothesized that contractile element potentiation was a significant contributor to stretch-induced muscular performance under these conditions.

potentiation; preforce; isokinetic squat; contraction history

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THE PROGRESSIVE EVOLUTION of athletic performance and specific conditioning techniques is dependent on a thorough understanding of those mechanisms underlying dynamic muscular function. Yet, the mechanisms most responsible for the contribution of the active prestretch to enhanced performance of skeletal muscle in stretch-shorten cycle (SSC) contraction patterns remain an issue of debate among researchers (2, 8, 29). Traditionally, it has been recognized that the higher forces arising during an eccentric stretch of the muscle-tendon complex establish a functional state, which in turn is able to facilitate its force-producing ability. In this context, restitution of elastic strain energy, myoelectric potentiation, interaction effects of contractile components with tendinous structures, and chemomechanical potentiation have all been identified as possible sources of the stretch-induced gains in muscle function (8, 9, 17).

However, it has also been proposed that, during dynamic multijoint movements, the benefits of these mechanisms are insignificant (6). Bobbert et al. (6) concluded that the work output of the musculature in the concentric phase of a SSC is much greater compared with a purely concentric contraction, simply because the concentric movement in a SSC commences

with a higher active muscle state and a correspondingly higher level of force. Thus it is argued that the mechanical work performed by the muscle for the early part of the movement is relatively greater for the prestretch condition, irrespective of the possible contributions from other processes. Indeed, it has been acknowledged that allowing a muscle to achieve a state of increased activation before release will significantly increase its ability to perform work during the initial concentric shortening (18).

Studies on isolated muscle preparations have enabled researchers to investigate the effects of prestretch under conditions in which differences in the force at the onset of the contraction are minimized. When concentric performance is compared between situations in which the pretension (transitional force) is achieved isometrically as opposed to an active stretch, there is evidence of potentiation of the contractile element (CE). This can result in significantly greater work output during the initial 500 ms of shortening after the prestretch condition (16). Similarly, in the forearm flexors of humans, Cavagna et al. (9) were not able to explain the enhanced work output seen in prestretch tests, in terms of force differences at the onset of shortening. Differences in potential elastic energy due to differences in force were able to account for only ~50% of the observed augmentation to performance. Again it was suggested that stretching of the muscle-tendon complex potentiated the CE, such that it was able to produce more force for a given muscle length and corresponding shortening velocity. This phenomenon has also been effectively reproduced in single-fiber studies and appears to be most prevalent at muscle lengths above optimum (15, 26). Recent evidence suggests that this form of CE potentiation may result from sarcomere instabilities due to the nonuniform distribution of stretch within the fiber [for a brief review, see Morgan (25)].

It was the focus of this research to try to distinguish the relative contribution of mechanisms demonstrated to be of importance to muscle shortening under controlled *in vitro* situations to human performance during more functional movement patterns. If the overriding contribution of a prestretch is merely the attainment of a highly activated muscle state before shortening, then there should be little or no relationship between contraction history and concentric performance for a given starting force. Specifically, this study examined the quantitative effects of an eccentric stretch, compared with an isometric preload, on the mechanical work measured during the concentric phase of a squat movement performed on an isokinetic dynamometer.

## METHODS

### *Subjects*

Forty male subjects with a minimum of 12 mo of weight-training experience and an ability to squat a load of at least 1.5 times their body mass were recruited as subjects. All subjects were drawn from a variety of sporting backgrounds, which predominantly involved the lower body. Their mean age, height, and weight were  $23 \pm 1$  yr,  $179 \pm 3$  cm, and  $77.2 \pm 7.1$  kg, respectively. Before testing, all subjects attended a familiarization session, which involved the performance of all test items. The study was approved by the Ethics Committee of Southern Cross University, and each subject signed a written consent form before participation in the project.

### *Overview of Testing Protocol*

All tests were performed in a single session, and subjects were asked to refrain from all lower body training for the 3 days before testing. Before each session, a standardized warm-up was employed. It consisted of a 10-min stationary cycle at 60 W and then specific lower body stretches, followed by two sets of 10 repetitions of full squats with a 20-kg bar. To isolate any difference muscular contraction history may have on concentric work output, each subject was required to perform three separate isokinetic squats for which a common concentric movement pattern was employed. These were 1) a concentric-only (CO) squat, 2) a concentric squat preceded by an isometric preload (IS), and 3) a stretch-shorten cycle (SSC) squat. The isokinetic modality allowed for an effective comparison among tests, by minimizing differences in muscle shortening velocity and thus muscle lengths over each specified time frame. For all subjects, surface electromyograms (EMGs) for vastus medialis, vastus lateralis, and biceps femoris were collected during all the squat tests. The choice of single-joint quadriceps muscles reflected the need to isolate those musculotendinous units (MTUs) with relatively large length changes and hence the greatest potential for stretch-induced myoelectric response. To assess the contribution of muscles crossing the hip and ankle, surface EMGs for gluteus maximus, rectus femoris, and medial gastrocnemius were also recorded for 10 subjects (30). To serve as control items for both subject performance and EMG analysis, subjects also performed a standard countermovement jump (CMJ) and a maximal voluntary isometric contraction (MVIC) of the muscles for which EMG was recorded. These data were collected immediately before the first squat test, and within 3 min after the last squat test was finished. All relevant kinetic and kinematic data were displayed and recorded in real time by using the AMLAB system (Amlab International, Sydney, Australia), and calibration of all equipment was performed before all testing sessions.

### *Test Items*

**Squat tests.** All squats were performed on an isokinetic squat device (ISD), which was positioned directly over a force plate (type 9287, Kistler, Winterthur, Switzerland). At the start of each test, the charge amplifiers (type 9865A, Kistler) were reset to zero to negate the weight of the subject. The recording of force data commenced via a manual trigger before the start of each test. These data, sampled at a rate of 1,000 Hz, were collected for ~3–5 s, and the amplified voltage signal was transferred to an AMLAB System and stored to disk for analysis. The force platform was calibrated for vertical forces by placing a series of known weights on the plate and adjusting the calibration factor accordingly.

The ISD is a testing device that allows for standardized performance of the squat exercise by limiting movement to the frontal and sagittal plane while recording relevant kinetic data (Fig. 1). The ISD consisted of a Plyometric power system [PPS; Lismore, Australia; see Wilson et al. (33) for a full description], which was subsequently modified to allow it to function as a multijoint isokinetic dynamometer. The PPS was instrumented with a three-phase 4-kW motor, which was governed by an alternating current induction controller (PDL Electronic, Napier, New Zealand). A rotary encoder attached to the shaft of the motor provided the velocity feedback for the closed-loop system with the PDL controller. The response time of this system, i.e., zero to maximum torque, was achieved in under 10 ms. It provided standard bar acceleration of  $2,200\%/s^2$  of the maximum motor speed of 1,440 revolutions/min such that the time to criterion bar velocity (<200 ms) was limited only by the subject's individual performance. Bar-displacement data were provided by means of a rotational transducer (Celesco) fixed to the shaft of the PPS. It was calibrated by moving the bar through a known distance and adjusting the calibration gain as necessary.

Bar speed was set at a constant 0.40 m/s during all tests, based on the mean bar speed of a typical squat movement (24). The isokinetic protocol was used in order that, for a given time, muscle length changes occurring as a result of the movement would be somewhat similar across tests and their influence on contractile performance thus controlled. However, as with all in vivo isokinetic evaluations, there is a period of acceleration before the onset of the criterion velocity, with some associated impact artifact that cannot be controlled without excessive ramping of the acceleration speed. Because the shortening speed of the musculature for the acceleration phase of the movement would be different across the tests, it would be reasonable to expect that the isokinetic evaluation was influenced by small differences in muscle lengths. To maintain consistency of hip, knee, and ankle angles for the starting position for the CO and IS tests, and for the turnaround point for the SSC test, foot position was standardized by means of a marker cemented to the surface of the force plate. Subjects were positioned on the marker with a corresponding knee angle of  $90^\circ$  as measured with a manual goniometer. This knee angle was chosen because it has been reported as typical of those used in other studies (8) designed to assess functional lower body performance. Additionally, pilot testing revealed that the ability to generate force in this position was somewhat compromised because of the mechanical disadvantage of this knee angle. This was seen as important because it reduced the stress placed on the lower back of the subjects and possibly reduced the risk of back injury. To eliminate any possible contribution from prior muscle action, as a consequence of unloading or excessive preforce, force traces were examined immediately after testing and the trial was rejected if force levels deviated by  $>80$  N above or below the desired level. The order of testing was mixed for all subjects; however, because the IS squats required the transitional force data from SSC test, the IS squats were always performed after the SSC test. For all squat tests, subjects performed three trials with at least 3–5 min between trials and 5–8 min between tests.

**CO SQUAT (CO).** To determine the ability to generate force in a concentric movement, subjects performed an isokinetic squat for which only upward bar movement was allowed. Based on a technique previously described with respect to static jumps (32), the subject was restricted from utilizing any significant prestretch before the start of the tests by engaging the bottom stops of the ISD. This prevented downward movement of the bar. Subjects were instructed to exert

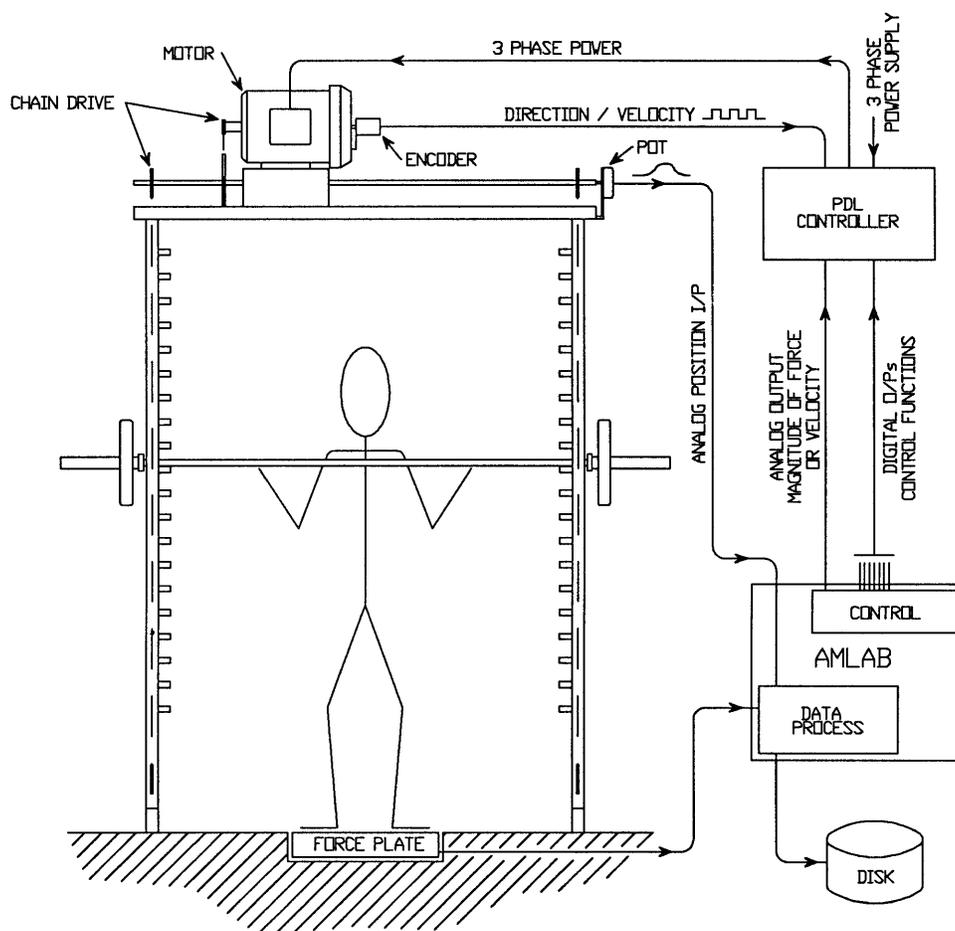


Fig. 1. Schematic of isokinetic squat device (ISD) depicting controller hardware and analog-to-digital data-collection system. POT, potentiometer; I/P, input; O/Ps, outputs; PDL controller, flux vector controller.

force as hard and fast as possible (4) in the vertical plane, and the test was repeated if pretension due to pressure on the bar exceeded 80 N in excess of subject's body weight. Thus the protocol did require subjects to maintain an isometric contraction to a level equivalent to body mass for a brief period (<1.5 s) before the start of the test.

**SSC SQUAT.** To assess the relative contribution of prestretch to dynamic movement, subjects performed an isokinetic squat preceded by a ballistic countermovement. With respect to concentric bar speed, this test was identical to the CO and IS tests and differed only in that subjects commenced the movement with the addition of an active stretch of the lower body musculature. To achieve this, software was used to disable the isokinetic mode of the ISD during the eccentric phase of the tests. As soon as the subject commenced upward movement, the isokinetic mode was automatically reengaged. A dynamic prestretch was a prerequisite for the validity of this test. To achieve this, subjects were instructed to perform the eccentric movement as fast as possible. To maintain the accuracy of the 90° knee joint angle turnaround point ( $\pm 3^\circ$ ), an auditory pretrigger controlled via software signaled to the subject to cease downward movement and immediately commence the concentric phase of the squat. If the subject did not satisfy these criteria, the test was repeated. Specific to each subject, the offset for the pretrigger was determined during the familiarization sessions and was used to account for the delay in turnaround resulting from the time lag due to individual reaction times and system momentum.

**IS SQUAT.** To address the issue of the effect of pretension subsequent to muscle shortening, an isokinetic concentric squat was preceded by an isometric contraction. This was

accomplished by using software to switch the ISD from isometric to isokinetic mode and was solely dependent on the subject achieving a preset level of force as measured via the force plate. Subjects were asked to exert force as hard and fast as possible (4) against the bar, which remained stationary (typically between 100–200 ms), until it automatically switched to isokinetic mode. At this point, subjects continued exerting maximal force for the duration of the concentric movement. The release force was individually determined from the mean transitional force at the 90° knee joint angle turnaround point during the three SSC tests.

At this point it must be noted that isokinetic bar speed does not necessarily imply isokinetic muscle shortening. The influence of muscle and skeletal architecture in multijoint movements will result in angular accelerations and decelerations of the hip, knee, and ankle joints with corresponding musculotendon length changes. Particularly at the onset of concentric movement of the bar, it is unlikely that all muscles will begin to shorten at the same time. However, such effects on testing were reduced by attempting to normalize body position at the start of the concentric phase.

#### Control Items

**CMJ.** To determine the extent of localized muscular fatigue as a consequence of the rigorous lower body testing protocol employed, all subjects were required to perform a standard CMJ before and after testing (31). For the CMJ, all subjects were required to perform three trials with 3 min of rest between trials. Maximum jump height was recorded by using a VerTec gauge (Questec, Northridge, CA). Starting position

for the CMJ required the subjects to place their hands on their hips and to retain this position until the end of the concentric phase of the jump. At this point they were allowed to raise their hand to displace the sliding bars of the VerTec. This procedure ensured that the contribution to performance from arm swing was negligible. For all jumping trials, subjects were instructed to jump for maximum height.

**MVIC.** MVIC of the muscles chosen for EMG analysis was also used to assess the integrity of the subjects' muscular condition and electrode-skin interface during testing. MVICs were conducted before and after the squat testing sessions, and subjects were required to perform a series of MVICs with as much effort as physically possible. They maintained each individual contraction for at least 4 s, during which time a 500-ms segment of maximal muscular activation was randomly recorded for further analysis.

### EMG

Before application of the electrodes, the surfaces were shaved, cleansed with alcohol, and mildly abraded, and a small amount of conductive gel was applied onto the electrode contact face. Pairs of silver-plated surface electrodes with a bipolar configuration were positioned parallel to the muscle fibers over the apparent belly of the muscles. The electrodes were taped and bandaged in position, to limit movement artifact, and remained untouched throughout the testing session. The EMG signal was fed directly into the alternating current-coupled input channels of the AMLAB system, which converted the analog signal to digital at 1,000 Hz. Software within AMLAB was used for the filtering of the EMG data. All signals were fed through a band-pass second-order Butterworth filter with high- and low-pass filters set at 3 and 500 Hz, respectively. The attenuation above the high-frequency corner and below the low-frequency corner was 12 dB/octave (40 dB/decade).

### Posttest Processing of Data

Data were averaged for all trials and subsequently normalized to the 100-, 200-, 300-, and 500-ms time frames after the start of the concentric movement across all test conditions. For the IS and CO tests, onset of concentric movement was defined as bar displacement of 3 mm. For the SSC test, it was 3 mm above the turnaround point at the end of the eccentric phase. Bar-displacement data were filtered by using a fourth-order Butterworth [cut-off frequency 39 Hz determined according to the methods of Yu and Hay (37)] and used in conjunction with force data to determine mechanical work for all tests. To allow comparisons among conditions and over time frames, EMG data were rectified, integrated, and normalized (i.e., expressed as a percent) to the corresponding period for the CO test (NIEMG). To account for possible influence due to electromechanical delay, a 30-ms offset before concentric bar movement was introduced to the EMG analysis. This epoch was chosen because in all three conditions the muscle-tendon complex was already under tension before shortening (35). All posttest processing was performed on an IBM-compatible Pentium (100 MHz) by using software developed within the Visual Basic 3.0 programming language (Microsoft).

### Statistical Methods

The intertrial reliability of all test items was assessed by using two different statistical methodologies: intraclass correlations and the SE of means. The method error was expressed as the coefficient of variation, i.e., equal to the SD of the mean difference in scores, expressed as a percentage of the combined means. Comparisons among the three squat conditions

were initially assessed by using a repeated-measures multivariate analysis of variance on all values for the 100-, 200-, 300-, and 500-ms periods after the concentric start. If a significant difference was found, post hoc comparisons were made by using a series of one-way repeated measures analysis of variance, with Helmert contrasts performed with SPSS (version 6.1) statistical analysis software. Statistical significance was accepted for an alpha level of 0.05.

## RESULTS

### Reliability of Test and Control Items

The intertrial reliability of both the control items and work values are depicted in Table 1. It is evident from these values that all measures show a high degree of repeatability within trials. The coefficient of variation for all of the tests is well within the 15% value recommended for biological measurement (1). On the basis of the similarity between the CMJ and NIEMG values for the MVICs before and after testing, it was assumed that the testing protocol undertaken did not adversely affect the subjects' performance and that it was reasonable to discount the effects of muscular fatigue on test performance.

### Comparison of Isokinetic Squat Tests

Figure 2 depicts the typical force-displacement curves produced by a subject performing the three tests. Bar position at the onset of concentric movement for the CO and IS tests was identical yet was on average  $3 \pm 3.7$  cm lower for the SSC test. Mean force at the start of concentric bar movement for the CO test was  $489 \pm 131$  N, which was significantly ( $P < 0.001$ ) lower than for the IS and SSC conditions. Comparison of the SSC and IS tests was contingent on the equality of the starting forces. It was subsequently shown that the mean force at the onset of shortening for the SSC and IS tests was  $1,193 \pm 222$  (SD) and  $1,169 \pm 216$  N, respectively, and

Table 1. Intertrial reliability for all test and control items

	Control Items	Test Items		
		CO test	IS test	SSC test
CMJ height	2.83 (0.91)			
NIEMG				
GM	5.2 (0.89)			
BF	8.8 (0.76)			
VM	6.9 (0.80)			
VL	10.1 (0.79)			
RF	6.3 (0.83)			
MG	5.7 (0.88)			
Work				
0-100 ms		9.7 (0.76)	8.8 (0.70)	9.5 (0.78)
0-200 ms		6.0 (0.85)	5.4 (0.83)	6.1 (0.85)
0-300 ms		5.3 (0.89)	5.0 (0.86)	5.9 (0.84)
0-500 ms		5.1 (0.88)	4.3 (0.92)	5.9 (0.86)

Values are coefficients of variation with intraclass correlation in parentheses. CO, concentric-only squat; IS, isometric squat; SSC, stretch-shorten cycle squat; CMJ, countermovement jump; NIEMG, normalized integrated EMG; GM, gluteus maximus; BF, biceps femoris; VM, vastus medialis; VL, vastus lateralis; RF, rectus femoris; MG, medial gastrocnemius.

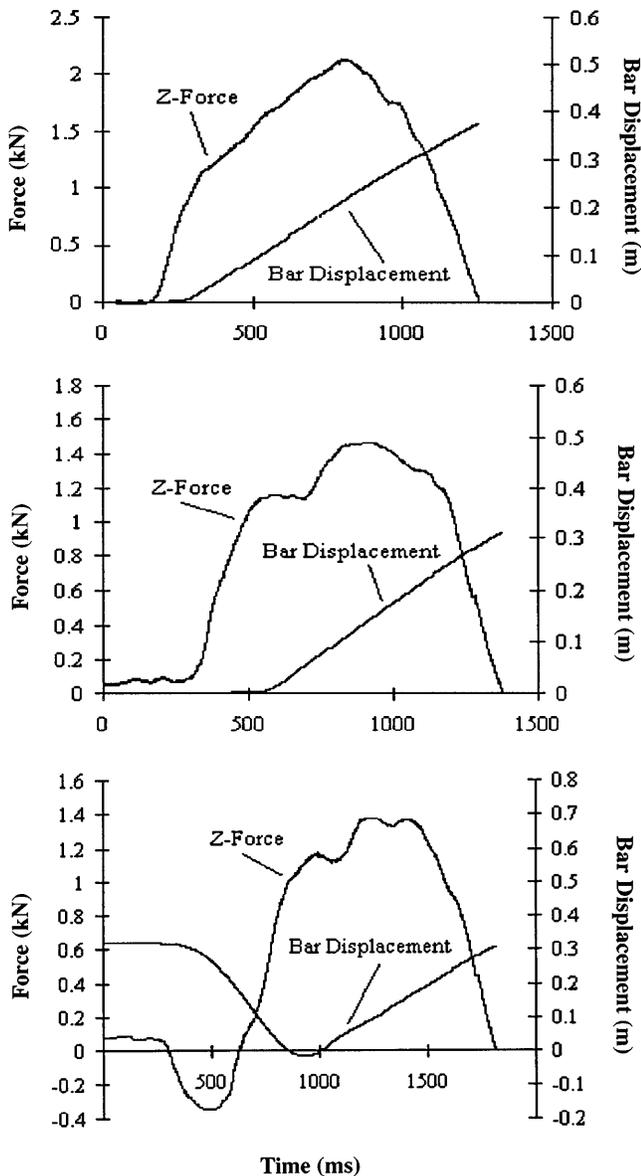


Fig. 2. Force-bar displacement curves for a representative subject for the 3 conditions: concentric-only (CO) squat test (top); isometric (IS) squat test (middle); and stretch-shorten cycle (SSC) squat test (bottom).

there was no significant difference ( $P = 0.37$ ) between these values. When the mechanical work output for the three conditions was compared, it was observed that both the IS and SSC conditions resulted in significantly greater muscular performance for the first 300 ms of the concentric phase compared with the CO squat (Table 2). Analysis also revealed that, if the squat was preceded by an active stretch rather than an isometric contraction, the subjects were initially able to produce more work, and these effects were seen over the first 300 ms of the concentric movement. Furthermore, if the mechanical work transients for each condition are examined (Fig. 3), it is clearly evident that, as a relative percentage of the total work, any early benefits from the active stretch and/or isometric preload are greatly

Table 2. Work for all tests over respective time frames

	CO Test	IS Test	SSC Test
Work 0–100 ms post**†‡	20.2 ± 6.5	31.8 ± 7.9	39.6 ± 13.3
Work 0–200 ms post**†‡	69.9 ± 18.8	87.0 ± 20.2	97.9 ± 23.1
Work 0–300 ms post*†§	129.7 ± 34.4	147.9 ± 34.7	154.8 ± 39.8
Work 0–500 ms post	268.9 ± 72.9	282.1 ± 73.6	280.2 ± 76.6

Values are means ± SD given in J. Post, after start of concentric movement. \*CO significantly different vs. IS,  $P < 0.001$ . †CO significantly different vs. SSC,  $P < 0.001$ . ‡IS significantly different vs. SSC,  $P < 0.001$ . §IS significantly different vs. SSC,  $P < 0.05$ .

reduced after the first 200–300 ms of the concentric action.

The power-time curves for one representative subject are depicted in Fig. 4. While the importance of the pretension is clearly observed by the more rapid development of power in the early stages of the IS test relative to the CO test, it appears as if the imposition of the stretch modifies the force-generating capacity of the musculature in such a way that cannot be achieved through an isometric contraction.

#### Muscular Activation

Across the three test conditions, there was a striking similarity among the activation patterns of all the muscles during the concentric phase of the squats (Fig. 5). There was no significant difference among any of the conditions, over any of the time periods, for any of the muscles tested. In the 200 ms before the start of the concentric phase, most muscle groups showed a general increase in muscle activation relative to the CO test. This is consistent with the relatively low level of muscle activation that would be necessary to support the subject's body weight before the start of the CO test. Importantly, there was no significant difference between the IS and SSC tests for the corresponding period.

#### DISCUSSION

The importance of pretension, before muscle shortening during in vivo research, has been repeatedly demon-

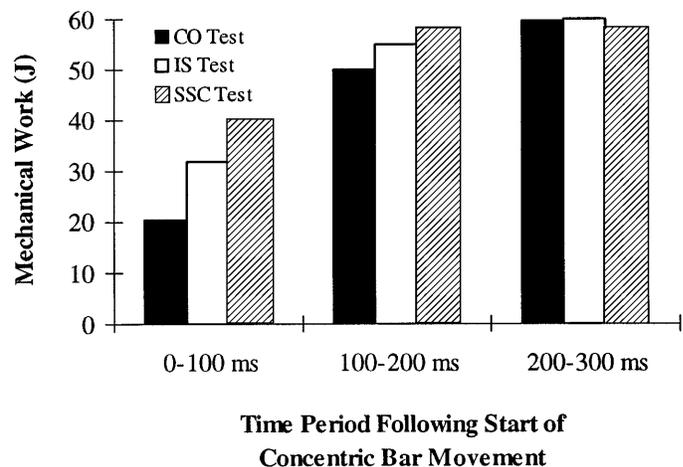


Fig. 3. Transient values of the mean mechanical work for all subjects over 3 test conditions (CO squat; IS; SSC squat).

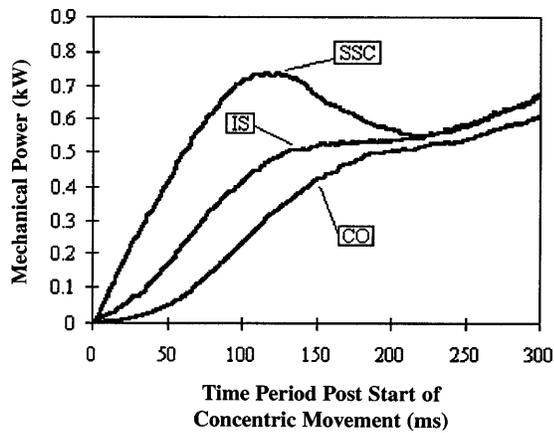


Fig. 4. Power-time curves from 1 representative subject for SSC squat test, IS squat test, and CO squat test.

strated (18, 19, 21, 28). Regardless of contraction history, if the concentric movement begins from a relatively higher level of force, our results show that this will add to the mechanical work of the muscles measured during the first 300 ms of shortening. This finding is supported by earlier research in isokinetic assessment (21, 28). These studies reported that concentric movements that were immediately preceded by either isometric or eccentric contractions led to greater concentric torque output than did purely concentric actions and that this effect was greatest early in the

range of motion of the muscle(s) being tested. With regard to the present movement pattern, it has been suggested that higher levels of muscle activation earlier in the movement will allow the muscles to produce greater force over a range of joint angles considered more favorable in terms of optimizing performance during these types of actions (6, 14).

However, our results also reveal that, whereas the level of force before the concentric phase of a multijoint movement is an important factor in determining subsequent performance, the manner in which this force is achieved must also be considered. An eccentric loading of the musculature resulted in significantly greater gains in performance than was evident as a consequence of preforce alone. Comparison of the SSC and IS tests shows that, for at least the first 200 ms of the squat, mechanical work was also dependent on the type of contraction preceding concentric bar movement. The following discussion will focus on the interpretation of these findings in relation to current theories on work enhancement due to active stretch of the musculature.

*Intermuscular Coordination*

For multijoint tasks, optimal performance is not merely constrained by the net force released by the MTUs, which are used to generate the movement. A specific pattern of intermuscular coordination is also necessary to effectively utilize the work capacity of the

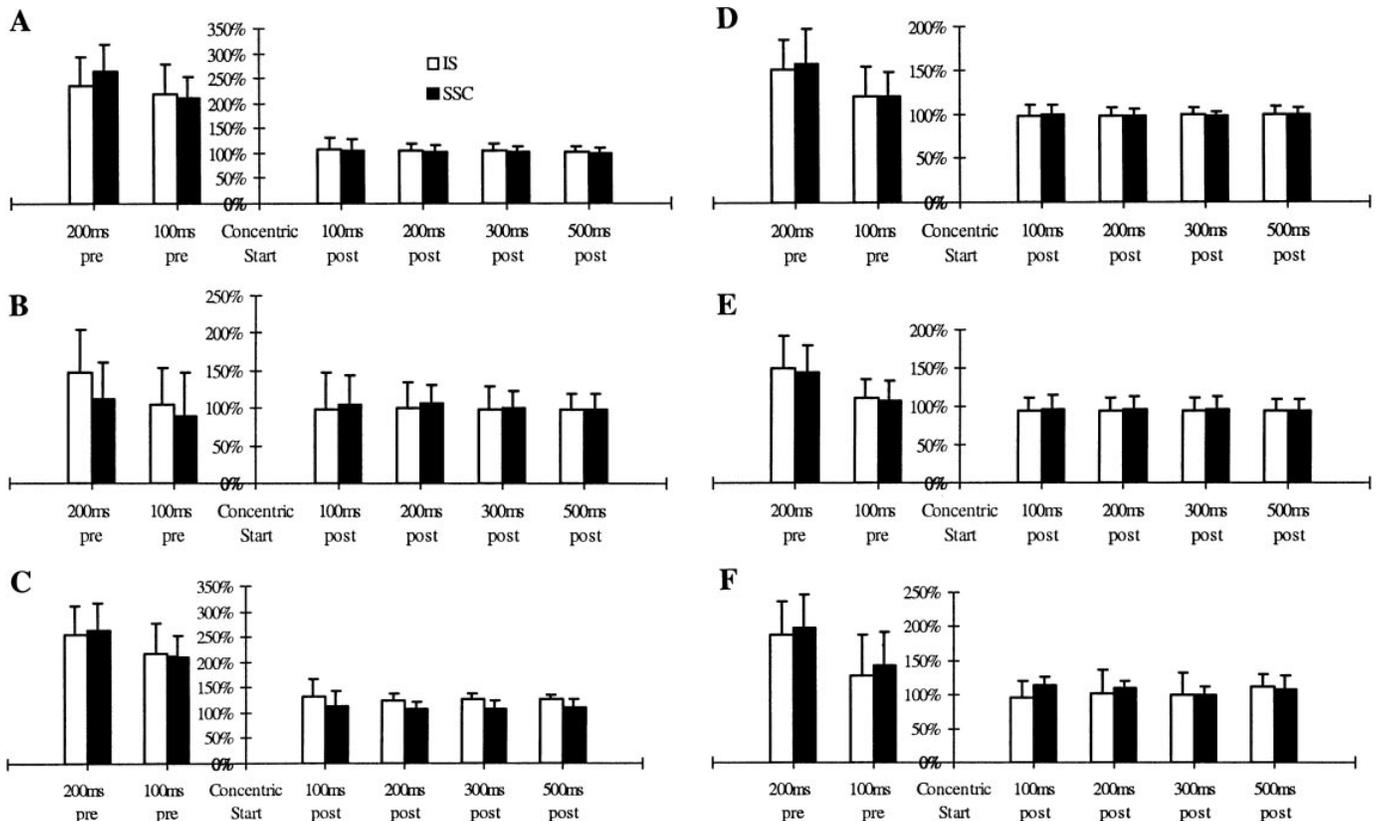


Fig. 5. Normalized integrated EMG for each muscle group, for respective time frames, before (pre) and after (post) start of concentric bar movement. (see METHODS for full explanation and subject numbers). Values are means  $\pm$  SD expressed as percentage of corresponding value for CO condition. A: gluteus maximus; B: biceps femoris; C: rectus femoris; D: vastus medialis; E: vastus lateralis; F: medial gastrocnemius.

muscles under these conditions (30). For the concentric portion of the tests, examination of the NIEMG data presented in Fig. 5, A–F, reveals that there was no significant difference among either the SSC, IS, or CO conditions. Figure 5 also shows that all muscles maintained a consistently high level of muscle activation for the duration of the assessment. The observed similarity of the concentric phase of the three tests presumably reflects the specific demands of the task.

In trained jumpers, a temporally ordered, proximal-to-distal sequence of muscle activation for the lower extremity musculature has been observed. This firing pattern coincides with the coactivation of mono- and biarticular muscles, which provides an effective mechanical framework for the transportation of energy delivered by this recruitment strategy. The end result is a coupling of joint powers such that vertical jumping performance is optimized and inappropriate acceleration of hip and knee joints is minimized (30). In this test, even though a similar posture to jumping was used, the movement speed of the bar was strictly controlled. This would effectively limit the angular acceleration of hip, knee, and ankle joints, a restriction that permitted simultaneous and near-maximal activation for all the muscles tested, regardless of the type of action that preceded the concentric movement. While small differences in activation patterns among the tests cannot be discounted, there is no evidence to support the notion that the enhanced performance of the SSC squat was due to changes in activation patterns for any of the muscles assessed.

#### *Myoelectric Contributions*

When jumps with and without prior stretch are compared, the greater jump height that is often observed in the prestretch jump may be accompanied by enhanced muscle activation, attributable to the rapid stretch of intrafusal muscle fibers and the resultant  $\alpha$ -afferent activation (8). The latency of the reflex response determines whether the augmentation to improved jump height is the result of direct contributions to the motorneuron pool or of increases in extrinsic muscular stiffness leading to an improved capacity to benefit from storage of potential elastic energy (8, 22). In some cases, it has been suggested that the myoelectric responses account for up to 85% of the increase in jump height after a countermovement (22).

Some doubts as to the importance of the stretch reflex have been raised by similar studies that report no difference in EMG recordings attributable to active stretch of the musculature (9, 27, 36). Such studies discount the effects of the stretch reflex on the basis of a saturation phenomenon, whereby, at maximal levels of contraction, the muscles become less responsive to brief increases in neural output (27, 36). Specifically, when comparing EMG activity for isokinetic knee extension tests across concentric, isometric preload and maximal eccentric contraction conditions, Svantesson et al. (28) reported unchanged or lower values when the movement was preceded by a muscle action. In the present study, the lack of significant differences among

NIEMG values among the tests would tend to suggest that, for the muscle groups tested, the contribution from myoelectric mechanisms to the superior work output for the SSC test was minimal.

#### *Restitution of Elastic Strain Energy*

The contribution of elastic strain energy to the improved muscular performance of the IS and SSC tests, relative to the CO test, cannot be discounted on the basis of the present findings. The attainment of forces in excess of 1,000 N before shortening for these experiments, which was over twice that measured for the CO squat, would result in significantly greater extension of the series elastic elements (SEEs) (2, 17). At the onset of shortening, elastic recoil of these elements would presumably add to the work output of the muscle-tendon complexes involved in these actions. However, it is impossible to determine its relative contribution for the different conditions.

Cavagna et al. (9, 10) and Bergel et al. (5) reported cases in which they were able to obtain equivalent forces before muscle shortening after both active stretch and isometric contractions. They claimed that this would invoke identical extension of the SEEs and thus the amount of energy stored within these components would be the same. Accordingly, in this series of experiments, the observed differences between the SSC and IS conditions cannot be explained by enhanced elastic energy release attributable to differences in force. With <2% separating the mean transitional forces for these tests, the effects of elastic recoil would be effectively limited between the conditions.

Nonetheless, a potential difference in the use of elastic strain energy may be explained by the concept of resonance. A number of authors have reported that maximal use of elastic strain energy occurs when the natural frequency of the MTU is equal to the movement frequency of the SSC action and hence the system is in resonance (3, 34). In essence, the concept of resonance suggests that elastic systems have a preferred rate of stretch in which optimal use of strain energy is achieved. This may contribute to both force output and/or the efficiency of energy consumption (3). Thus the use of elastic strain energy in a dynamic system is dependent not only on the extension of the SEE but also on the rate at which this extension occurs. The duration of the eccentric phase of the SSC test ranged between 500 and 800 ms, much longer than the 100–300 ms typically required to achieve the desired transition force for the IS test. Because this was an aspect of testing that was not controlled between the IS and SSC conditions, it is conceivable that the difference in the initial concentric performance enhancement may be explained, to some extent, by the SSC action involving a rate of SEE extension that was closer to achieving resonance compared with the IS condition.

#### *Interaction Effects of Tendinous Recoil on Contractile Dynamics*

It has been shown that the contribution of the contractile element to work production during SSC move-

ments is influenced by the effects of tendinous recoil (16, 17, 20). Higher forces at the onset of shortening for the IS and SSC squats relative to the CO test would introduce differences in both fiber length and fiber shortening velocity during the subsequent contraction (12, 16). Assuming that the similarity in the concentric starting point across the tests resulted in comparatively equal MTU lengths, the additional force present at the start of the IS and SSC tests would mean relatively greater tendinous extension with less myofibrillar displacement (2). Thus there exists the potential for the fibers in the SSC and IS squats to have been displaced less and thus be operating closer to an optimal length.

A similar argument is also feasible with respect to muscle force-velocity characteristics. The recoil of tendinous structure, associated with the release of elastic energy for the IS and SSC squats, would suggest that the velocity of CE shortening would be relatively lower with corresponding enhancement to force production. This contrasts with the situation during the CO test, in which a higher velocity of CE element shortening may have occurred initially to extend the elastic elements of the SEE. Hence the force-velocity relationship would dictate that force production of the CE would be compromised. In comparison, the SSC and IS squats commenced with similar transitional forces. Assuming that a constant bar velocity also translated to similar CE shortening velocities across the SSC and IS conditions, it is difficult to explain the SSC-IS difference solely on the basis of different CE velocities.

#### *Potential of the Contractile Element*

The nature of the differences between the SSC and IS tests led to the hypothesis that the improved capacity for mechanical work, as a result of the stretch, was primarily due to the enhanced performance of the CE. These findings support earlier experiments conducted on intact muscle-tendon complexes (9, 12), isolated amphibian and rat muscles (9, 16, 17), and single muscle fibers (15, 26). This interpretation is based on the regulation of force levels across the present tests, which is thought to rule out any discussion based on difference in elastic potential energy (5) as well as differences due to the interaction of SEE and CE at the onset of shortening (17). Interestingly, the observed augmentation to work output of the SSC test over the IS test (4–19% over the first 300 ms) is in close agreement with those potentiation values and transients (2–16% over the first 500 ms) observed *in vitro* by using comparable protocols (16, 17).

The fact that the early benefits from the stretch were not seen 500 ms after the concentric start may be evidence of the transient nature of muscle potentiation (9, 10, 16, 17, 25). However, the force differences initially induced by potentiation of the contractile element can also result in minor secondary differences in CE length and shortening velocity (17). Thus it could also be argued that, after 300 ms, the small differences in CE dynamics attributable to potentiation were no longer significant. The convergence of mechanical work

values also suggests that the influence of differences in contractile element length at the start of the concentric phase was minimal because large CE length differences would presumably invoke variations in work that persisted for the duration of the analysis (Figs. 3 and 4).

#### *Practical Implications*

In an attempt to more accurately determine maximal dynamic muscle performance, the attainment of muscle tension before shortening has long been recognized by researchers in the field of isokinetic evaluation (19, 21, 28). By allowing a muscle(s) to achieve maximal tension earlier in a contraction, for a given movement range, preforce techniques allow the assessment of muscle function with a correspondingly greater isokinetic evaluation period and with less signal distortion due to impact artifact.

In terms of performance enhancement, the significance of prior muscle tension may be fully realized when one considers how such information could be used to optimize muscular output after active stretch. Plyometric conditioning techniques and sports such as sprinting and ski jumping are typically characterized by rapid SSC movements, in which the application of force occurs within 200 ms. It would seem reasonable to assume that modifications to technical development could be justified, on the basis of ensuring that the timing of the movement was appropriate in view of maximizing transitional force. Within the limitations of the sport, this would mean that the eccentric deceleration during the SSC occurred rapidly and as close to the turnaround point as physically possible. It could be said that plyometric conditioning techniques, which stress muscle activation before contact, minimal contact time, and explosive muscular contractions, are designed to achieve this goal (7). It has been shown that successful performers of such tasks are characterized by contraction patterns that reflect such aims (23).

For cyclic SSC activities such as hopping, the eccentric prestretch seen on landing is an inevitable consequence of the preceding contraction. The existence of a contributor to concentric work output, in the absence of any significant increase in concentric EMG activity, reinforces suggestions that CE potentiation incurs minimal, additional metabolic cost (10). In turn, these findings offer indirect support to the claims that such a mechanism is able to contribute to those efficiency values reported for running, walking, and jumping that are in excess of that expected from approximations of muscle efficiency (11). De Haan et al. (13) concluded that, on the basis of very similar estimates of energy consumption between prestretch and preisometric contractions imposed on the medial gastrocnemius MTU of rats, the higher efficiency values exhibited during the prestretch contractions were attributable, in some part, to a nonelastic source of additional work. Such a hypothesis is attractive when one considers that even small savings to the metabolic cost of muscle shortening during such activities is cumulative over many repeated contractions.

### Conclusion

The results of this study clearly reinforce the importance of contraction history before muscle shortening. When distinguishing between the concentric and preforce (SSC and IS) tests, it was not possible to delineate the contribution of force alone from those mechanisms that arise as a direct result of the applied force. Therefore, it was concluded that higher transitional force at the commencement of the concentric movement in the preforce conditions may have elicited greater positive work due to a combination of several factors. These included a relatively greater active muscle state, the restitution of elastic strain energy, and the effects of tendon recoil on muscle-tendon interaction. There appeared to be minimal influence from stretch-induced reflex activity. Nevertheless, the importance of pre-tension does present the opportunity for more discriminate assessment of athletic function, with a view to improving both the performance and training of these movements.

The present findings also suggest that CE potentiation may contribute significantly to stretch-induced work enhancement during multijoint SSC movements, particularly if the duration of the concentric phase of these contractions is under 300 ms. While these results provide functional evidence in support of those findings previously described with respect to *in vitro* research, there is a need for a more detailed investigation into the practical relevance of such mechanisms. In particular, it would be worthwhile to examine the response of CE potentiation to training stimuli as well as examine its relationship to eccentric muscle length *in vivo*.

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