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Stretch Shorten Cycle Performance: Detrimental Effects of Not Equating the Natural and Movement Frequencies

Greg J. Wilson, Aron J. Murphy, Andrew D. Walshe, and Kevin Ness

This study aimed to assess whether the benefits associated with stretch shorten cycle (SSC) movements required the movement frequency to be in resonance with the natural frequency of the elastic structures. Seventeen untrained participants performed SSC and concentric bench press throws. Further, quasi-static muscular actions were also performed in which a brief perturbation was applied to the bar with the resulting damped oscillations providing natural frequency data. It was observed that prior stretch did not facilitate concentric performance. Further, there were large significant differences between the natural frequency of the musculo-tendinous system and the frequency of the SSC movements. The authors hypothesize that the failure to achieve resonance contributed to the poor performance achieved in the SSC actions.

Key words: performance, exercise economy, motor control

Most movements, such as running, jumping, throwing, striking, and lifting are a result of an eccentric action promptly followed by a concentric action. Such a movement sequence is typically referred to as a stretch shorten cycle (SSC), as the muscle is stretched prior to being shortened. SSC movements are common, because they augment the concentric phase of the activity through a more effective transmission of initial force, the use of elastic strain energy, and additional reflexively induced neural input (Bosco, Tarkka, & Komi, 1982; Komi, 1984; Wilson, Wood, & Elliott, 1991). In maximizing the benefits of using prior stretch, several authors have suggested that the movement frequency of the SSC portion of the action should be matched with the natural frequency of the musculo-tendinous system (Bach, Chapman, & Calvert, 1983; Denoth, 1985; Taylor, 1985; Wilson et al., 1991), because the system then operates in resonance; the authors reported that optimal benefits of the SSC were then achieved.

Bach et al. (1983) performed a study whereby participants were required to perform a cyclical contraction of the calf musculature over a series of movement frequencies which varied in 0.5 Hz steps from 2.5 to 5.5 Hz. These researchers observed that the muscular effort associated with performing oscillations about the ankle joint, at a given force, was minimized when participants performed at their natural frequency (3.3 ± 0.15 Hz). Further, these researchers re-analyzed several studies and reported that the frequency of the landing impulse of performance by participants in repetitive hopping, jumping, and fatigued running showed close resemblance to the estimated natural frequency of their elastic structures. Cavagna, Franzetti, Heglund, and Willems (1988) observed that, at low speeds of running and in trotting, the apparent natural frequency of the body was practically equal to the freely chosen step frequency. Denoth (1985) designed a mechanical model which demonstrated that the maximal performance in the vertical throw of a shot occurred when the frequency of the movement corresponded to the natural frequency of the series elastic mass system, and, hence, the system was in resonance.

Taylor (1985) observed that participants who hopped utilized a nearly constant movement frequency over a wide range of speeds (0.25–2.2 $m \cdot s^{-1}$). Similar observations have also been made with hopping kangaroos (Dawson & Taylor, 1973) and galloping quadrupeds (Heglund, Taylor, & McMahon, 1984). At the preferred hopping frequency Taylor (1985) reported that the role of elastic strain energy was maximized and that of metabolic energy was minimized. Forcing participants to hop at frequencies other than the preferred frequency greatly reduced the use of elastic strain energy in movement. Taylor rationalized the preferred movement frequency as being matched to the natural frequency of the "whole body spring." This author concluded: "The behavior of

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Greg J. Wilson, Aron J. Murphy, and Andrew D. Walshe are with the Centre for Exercise Science and Sport Management at Southern Cross University, Australia. Kevin Ness is with the Physics Department at James Cook University, Australia.

this system is what would be predicted for a tuned spring with its resonant frequency at the natural hopping frequency." (Taylor, 1985, p. 257).

Wilson et al. (1991) observed that experienced weight trainers performed near maximal bench press lifts that matched the participants' natural and movement frequencies. Consequently their musculo-tendinous systems were in resonance. Because all participants were reported to be operating in resonance, it was not possible to establish the importance of resonance to the performance benefits associated with the SSC.

While the above studies provide some interesting evidence supporting the performance of SSC actions in resonance, it is by no means overwhelming. The present study aims to follow this research and examine the performance benefits derived from prior stretch when upper body SSC movements of varying movement frequency are performed by relatively untrained individuals. In structuring such a study it is conceivable that at least some of the SSC movements may not be performed in resonance.

Method

Participants

Seventeen male university students (*M* age = 21.7 years, *SD* = 6.9; *M* height = 178.1 cm, *SD* = 5; *M* body mass = 73.5 kg, *SD* = 10.5; and *M* maximum bench press lifts = 67.1 kg, *SD* = 13.6), who were not experienced in the performance tasks, volunteered to participate in this study. The study was approved by the Ethics Committee of Southern Cross University, and participants signed a written informed consent form prior to participating in the study.

Apparatus

Plyometric Power System. To perform the tests, participants used the Plyometric Power System (Plyopower Technologies, Lismore, Australia), an isotonic load system which allows for the safe performance of dynamic bench press throws with a loaded bar while recording relevant kinematic data at approximately 3000 Hz (Wilson et al., 1991; Wilson, Newton, Murphy, & Humphries, 1993). The machine allows only vertical bar movements, and mechanical stops control bar at 0.02 m increments (see Figure 1). Linear bearings, attached to either end of the bar, allowed it to slide about two hardened axle steel shafts with low friction. The system also incorporates an electro-magnetic braking unit which, when engaged, holds the bar in a stationary position at any point in the 2.0-m range of motion. A rotary encoder attached to the machine produced pulses indicating bar displacement. One pulse was generated for each 0.00106 m of bar movement. Each pulse was recorded by a counter timer board installed in a 486DX IBM-compatible computer capable of measuring pulse frequencies up to 1 MHz; computer software calculated displacement and velocity. Velocity data were derived by timing the delay between consecutive pulses which corresponded to bar displacement. This data was smoothed using a fourth- order Butterworth filter set at 16 Hz. A 100000-Hz pulse frequency timed this delay, providing a timing accuracy to 10 μs. The system was calibrated prior to use by measuring the total number of pulses produced as the bar was moved through its full vertical range (2.0 m).

Force Platform. A rigid bench, secured by four bolts directly into a force platform, recorded vertical force during the performance tests and oscillations (Kistler 9287 Winterthur, Switzerland; see Figure 1). The surface of the bench was solid, with negligible padding, to prevent attenuation of the developed forces. At the start of each test, the force plate was reset to zero to negate the weight of the subject and the bench. This allowed for a more sensitive recording of the force produced during the tests. Recording commenced via a manual trigger prior to the start of each test. Force data, sampled at a rate of 600 Hz, were collected for 3 s by a DAS16 analogue to digital card installed in a 486DX IBM-compatible computer. The force platform was calibrated before and after each testing session. The kinetic data from the force platform and kinematic data from the Plyometric Power System were recorded simultaneously.

Design and Procedure

Prior to initial testing, participants were familiarized with all tests. Testing took place on 2 separate days, within a 1-week period. Participants received a minimum of 72 hrs rest between each test day and were instructed to abstain from any strenuous upper body activities for the duration of testing.

On the first day of testing, participants' maximum bench press, in a SSC movement, was determined using the procedures of Wilson et al. (1991). The bench press is a popular weight training exercise performed primarily to develop upper body strength. To perform the bench press, one extends the forearms at the elbow, adducting the arm horizontaly, while lying supine on a bench. During testing, participants used an eccentric action to lower the bar from arms' length until it touched the chest at nipple level and a concentric action to lift it promptly to arms' length. Participants performed the bench press with progressively increasing loads, until they achieved the maximum load. Initially, large weight increments of 10 to 15 kg were used. As participants reached the maximum load, smaller increments of 2.5 to 5 kg were added until participants failed to lift the load. This procedure generally required no more than four at-

tempts, separated by 3-minute rest intervals. The maximum bench press was determined so that participants could complete the performance and natural frequency tests using loads relative to the maximum. Additionally, an oscillation technique was used to determine the natural frequency of the musculo-tendinous unit for loads 30% and 60% of the maximum.

On the second day of testing, the tests administered were: (1) SSC bench press throws performed with loads of 30% and 60% of the maximum bench press lift; and (2) purely concentric bench press throws at loads of 30% and 60% of the maximum. The testing order was completely random.

Prior to each test session, all participants performed a standard warm-up and stretching exercise which consisted of light bench press lifts, upper body muscle extension, and several sub-maximal trials of the tests. For the natural frequency tests, participants performed three trials at each load and two trials each for the concentric and SSC bench press throws (Murphy, Wilson, & Pryor, 1994; Wilson, Murphy, & Pryor, 1994). In both cases the results were averaged. Particiants performed only one trial for the maximum bench press lift, as is standard for this test (Berger, 1962; Wilson, Elliott, & Wood, 1992). A 3-min rest period was imposed between repeat trials and tests.

Performance Measure

The SSC and concentric performance tests were conducted in a bench-press-type movement using the Plyometric Power System positioned over a force platform to record vertical forces. For the bench press throws, participants lay in a bench-press position and, extending the forearms at the elbows and adducting the arms (see Figure 1), rapidly threw the bar for height. For all tests, participants were instructed to keep their feet on the bench. Hand position on the bar was standardized as the distance between the elbows, with the shoulder complex abducted to 90°.

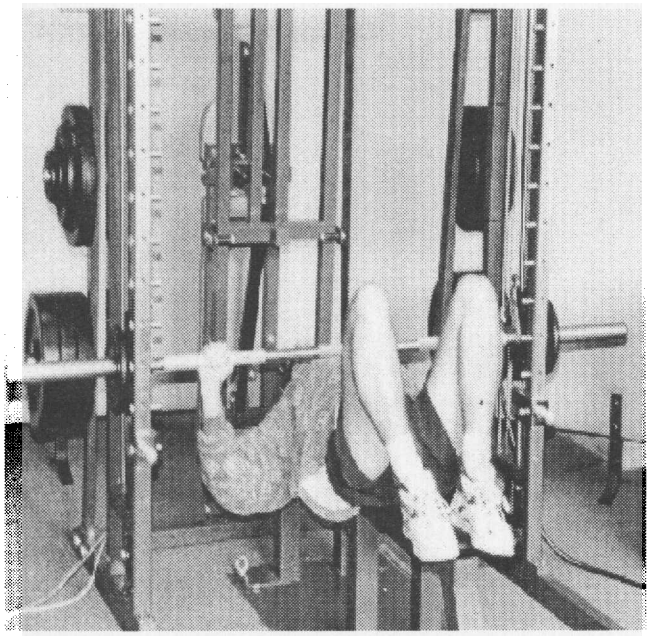

Figure 1. Experimental set up for the SSC and concentric bench press throws.

Concentric tests. Participants lay in the bench-press position with 30 or 60% of the maximum load held in position just above the chest by the mechanical stops of the Plyometric Power System. Participants were instructed to throw the bar for maximum height. At maximum height, the bar was halted by the electro-magnetic braking mechanism of the Plyometric Power System so that participants did not have to catch the returning bar.

SSC tests. These tests were performed in an identical fashion to their concentric equivalents with the exception that the bar was initially held at arms length and participants performed an eccentric action prior to the concentric movement. A guide was placed on the shaft of the Plyometric Power System 5 cm above the bottom. For a trial to be considered for further analysis, the bar had to contact the guide without hitting the bottom stops of the machine. This ensured that the maximum difference in starting position between the two tests was 5 cm. The movement frequency for the SSC action was left to the discretion of the participants.

Performance benefits derived from prior stretch were determined by comparing the work performed during the initial 370 ms of the SSC concentric phase and the concentric bench press. In each condition, the first upward movement of the bar determined commencement of the concentric phase. The work was quantified by determining the instantaneous power throughout the bench press actions by multiplying force by velocity and integrating this value with respect to time. Force data were collected by the force plate, while velocity data were recorded by the Plyometric Power System. Due to arm mass and minor body motions, the force as calculated by the plate will be slightly greater than the force applied against the bar. Nevertheless, this overestimation will presumably be consistent for all performance conditions. The 370 ms period was used, because it has been shown previously that the performance benefits derived from prior stretch in a bench press movement were dissipated within this period (Wilson et al., 1992; Wilson et al., 1991).

The movement frequency (f_m) of the SSC portion of the bench press throws was quantified based on the velocity profile of the movement. In line with research performed by Cavagna et al. (1988), the time between maximum negative linear bar velocity and zero velocity, when the bar momentarily achieves its lowest position, corresponded to one-quarter of the period of oscillation.

Hence, the movement frequencies for the 30 and 60% SSC bench press throws were calculated as follows:

$$f_m = 1/(4t)$$

where t is the period depicted in Figure 2.

Determination of Damped Natural Frequency

The natural frequency of the musculo-tendinous unit was determined using the procedures outlined in detail by Wilson et al. (1991; 1992; 1994). Briefly, this procedure involved an oscillation technique whereby the par-

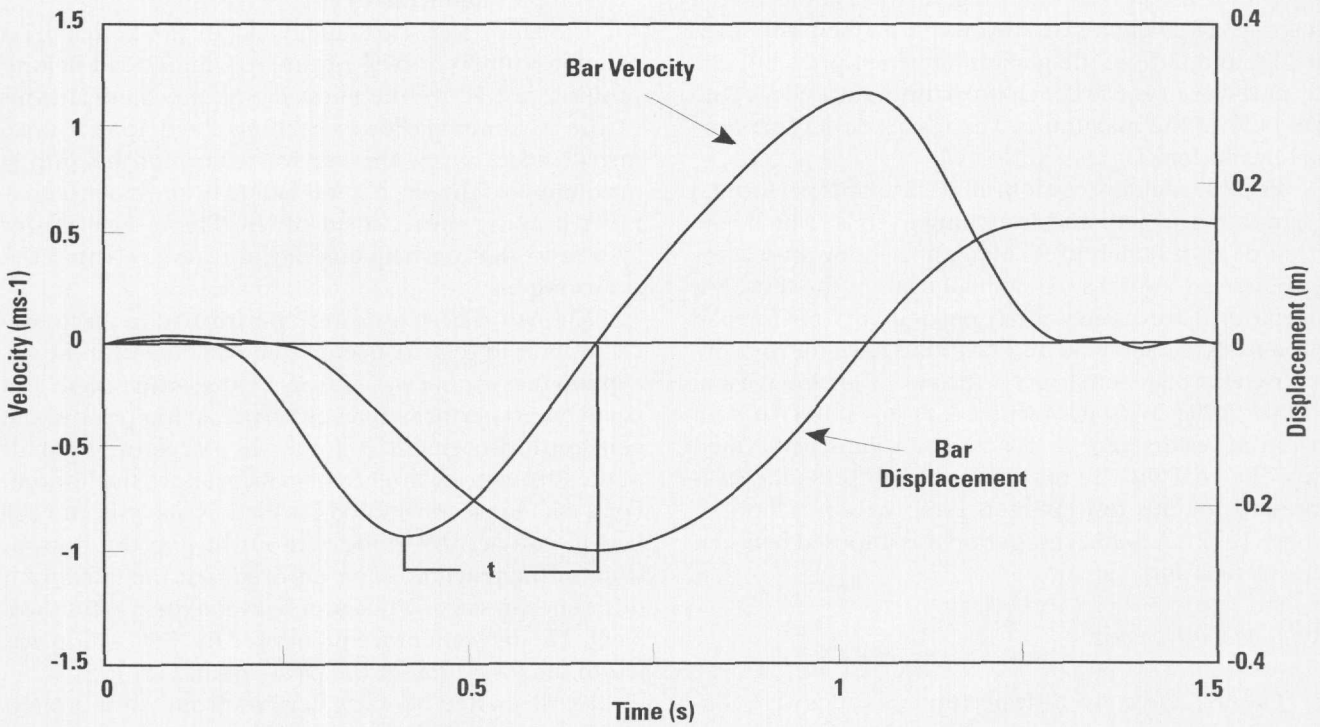

Figure 2. Portion of velocity-time and position-time curves of a stretch shorten cycle bench press throw performed with a 60% load by a representative subject (JB).

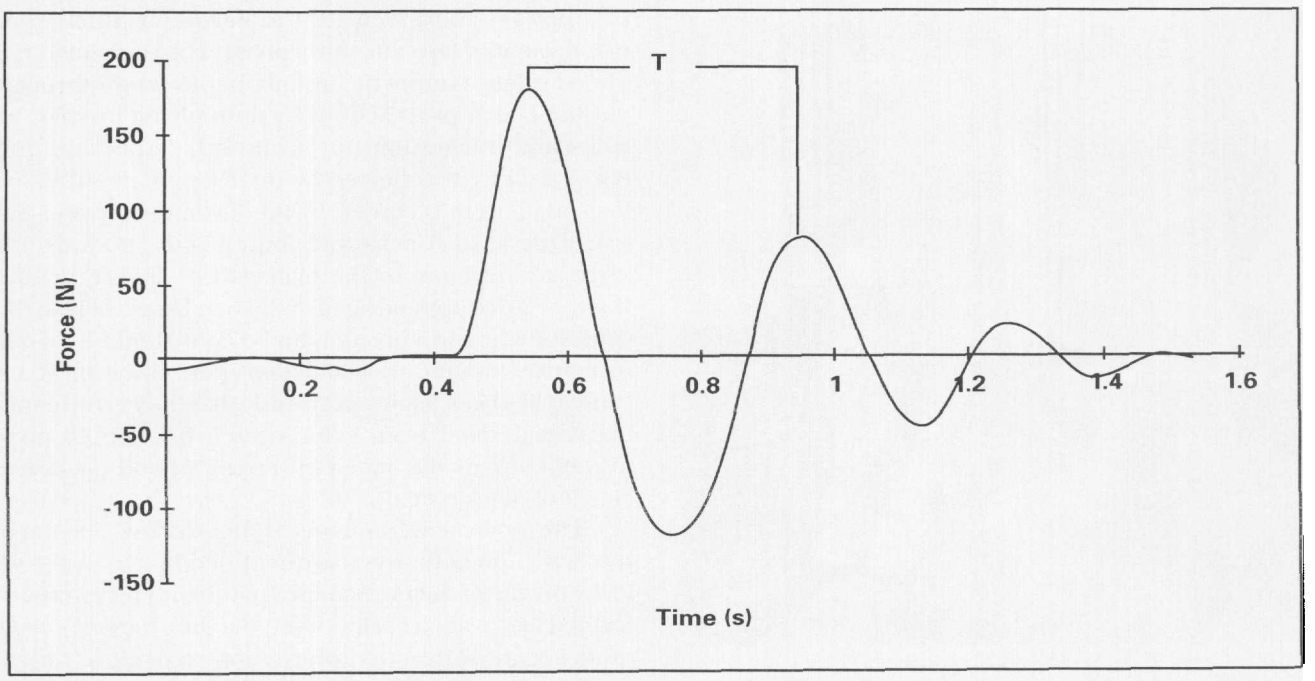

Figure 3. Representative force-time recording from the oscillation technique, used to determine damped natural frequency (f_d). T, period between successive force peaks, $f_d = 1/T$.

ticipants maintained a loaded free weight bar in an isometric bench press action approximately 8 cm above the chest. The participants held the bar steady in this position for approximately 0.6 s, after which an external force in the order of 100 N was applied briefly (150–200 ms) to the middle of the bar with a downward push of the experimenter's hands. Such a procedure to perturbate the system has been used by Shorten (1987) and Wilson et al. (1991; 1992; 1994). This results in a slight variation in the magnitude of the perturbation between trials; however, it does not appear to vary the natural frequency values obtained, because an elastic system oscillates at its natural frequency independent of the magnitude of the applied perturbation. The force plate underneath the bench recorded the resulting damped oscillations (see Figure 3).

The participants were instructed to maintain a constant level of muscular activity and not respond to the perturbation during the oscillation of the bar. This "do not intervene" strategy has been used previously in an attempt to limit the neural responses to an applied perturbation to only those that are involuntary (Gottlieb, & Agarwal, 1988; Wilson et al., 1991). Three oscillations trials were performed at loads of 30% and 60% of maximum.

Data Analysis

A two-way, repeated-measures variance analysis was performed between the concentric and SSC performance tests at each load to determine the benefits to performance derived from prior stretch. Such a test was also employed to examine whether there were statistical differences between the natural frequency of the musculo-tendinous system and movement frequencies of the various SSC tests. Statistical significance was accepted at an alpha level of .05.

Table 1. Inter-trial coefficient of variation for the tests ($N = 17$)

Variable	%
Maximum concentric velocity	1.8
Maximum SSC velocity	1.9
Concentric work (370 ms)	6.0
SSC work (370 ms)	7.6
Movement frequency	14.5
Natural frequency	3.4

Note. SSC = Stretch Shorten Cycle.

Table 2. Performance test means and standard deviations ($N = 17$)

Variable	Concentric		SSC	
	M	*SD*	*M*	*SD*
30% initial work (J)	178.5	28.3	170.4	28.3
30% maximum velocity ($m \cdot s^{-1}$)	1.764	.100	1.763	.103
60% initial work (J)	167.0	33.8	168.8	38.8
60% maximum velocity ($m \cdot s^{-1}$)	1.222	.109	1.216	.114

Note. SSC = Stretch Shorten Cycle.

Results

Reliability was established by calculating the variation coefficient between the trials performed. These data are outlined in Table 1 and show that most of the performance measures were highly reliable. The results of the various concentric and SSC tests are outlined in Table 2. In both the 30% and 60% bench press throws, performance, in terms of initial work done or maximum bar velocity, was similar in the concentric condition as compared to the SSC action (effect sizes < 0.3; see Table 2). In accordance with the force-velocity relationship, the maximum velocity for the 30% load conditions were significantly higher than for the 60% load, $F(1,32) = 231$, $p < .05$; effect size = 5.2.

To examine the resonance theory, natural and movement frequencies were compared for each load condition. For the 30% load, the natural frequency was 2.2 ± 0.2 Hz, while the movement frequency was 1.2 ± 0.2 Hz. In the 60% load condition, the natural frequency was 2.1 ± 0.2 Hz, while the movement frequency was 1.0 ± 0.2 Hz. There were significant differences between the natural frequency of the musculo-tendinous unit and the movement frequencies of the SSC actions, in both the 30% and 60% load conditions, $F(1,16) = 281$, $p < .05$, effect size = 5.0; $F(1,16) = 732$, $p < .05$, effect size = 5.5, respectively, with the natural frequencies substantially greater than the movement frequencies. Interestingly, the natural frequency for the 30% load condition was similar to the 60% condition, $F(1,32) = 0.183$, $p > .05$, effect size = 0.5. However, the movement frequency for the 30% load condition was significantly higher than the movement frequency for the 60% load condition, $F(1,32) = 7.86$, $p < .05$, effect size = 1.0.

Discussion

In both the 30% and 60% load conditions, prior stretch did not facilitate concentric performance. Such a result was surprising, because a number of studies have reported that prior stretch facilitates concentric performance in both upper (Bober, Jaskolski, & Nowacki, 1980; Chapman, Caldwell, & Selbie, 1985; Van Leemputte, Spaepen, Willems, & Stijnen, 1983; Wilson

et al., 1991) and lower body movements (Asmussen & Bonde-Petersen, 1974; Cavagna, Saibene, & Margaria, 1964; Komi & Bosco, 1978).

The natural frequency of the musculo-tendinous unit and movement frequency of the SSC actions were significantly different for both the 30% and 60% load conditions. The discrepancy between the natural and movement frequencies was 1.1 Hz for the 60% load and 1.0 Hz for the 30% load condition. These discrepancies correspond to effect sizes in the order of 5. As such, the SSC bench press throws were not performed in resonance with the underlying frequency of the musculo-tendinous system, with the movement frequencies substantially lower than the corresponding natural frequencies. The authors believe that the failure to achieve resonance has resulted in the SSC action being ineffective in enhancing concentric performance. Such a proposition is supported by previous research which has indicated that the performance benefits derived from prior stretch from a variety of SSC movements, including the bench press, were maximized when the natural and movement frequencies were matched, and, hence, resonance was achieved (Bach et al., 1983; Denoth, 1985; Taylor, 1985; Wilson et al., 1991).

It is interesting to contrast the results of the current study to Wilson et al. (1991), who reported that prior stretch in a bench press action resulted in a 15.6% augmentation to initial concentric impulse. In this study the participants were reported to operate in resonance with their underlying elastic structures. The main difference between the present study and Wilson et al. (1991) was the experience level of the participants. In the present study novice participants were used, whereas in the study by Wilson et al. (1991) the mean training age of the participants was 5.3 years, $SD = 1.9$. Perhaps the increased experience with the movement task allowed participants the opportunity to progressively modify their movement frequency to match their musculatures' natural frequency and, hence, eventually achieve resonance. On the basis on the present results one can only speculate; however, it may well be the case that attaining resonance is an important feature of skill learning in SSC movements, and further research should be directed toward this end.

The SSC and concentric bench press throws are seen as analogous to the popular static versus counter-movement jumping movement paradigm (Asmussen & Bonde-Petersen, 1974; Komi & Bosco, 1978). The use of prior stretch in the jumping paradigm typically results in an approximately 12% increase in vertical jump height (Asmussen & Bonde-Petersen, 1974; Komi & Bosco, 1978). The main difference between the bench press throw and vertical jumping movement paradigms is that while dynamic SSC lower body actions such as vertical jumping are common and a well learned skill, a bench press throwing action is a relatively novel task in comparison.

Interestingly, in re-analyzing previous research using the popular jumping movement paradigm, it is observed that the movement frequency of SSC jumping actions appears to be in the 2- to 3-Hz range (Bosco & Komi, 1982; Bosco et al., 1982; Komi & Bosco, 1978). These movement frequencies are within the 1- to 3-Hz natural frequency range reported by Greene and McMahon (1983) for a loaded oscillatory movement performed in a posture specific to vertical jumping. They are also similar to the 2.5- to 3.6-Hz natural frequency range reported by Cavagna (1970) for free oscillations recorded from participants after landing, without bending the knees, with a sustained contraction of the calf musculature. Consequently, it appears likely that SSC jumping actions occur in resonance with the natural frequency of the musculo-tendinous system, and this may account for their effectiveness. Such a result may be due to the fact that dynamic lower body SSC actions are well learned, with opportunity for individuals to progressively modify their movement frequency to tune into their natural frequency. Alternatively, a natural frequency similar to the common movement frequency employed in running and jumping may be a quality that has evolved over time. Irrespective of the mode through which resonance in the lower body occurs, based on the results of this study in combination with previous results, it is conceivable that optimal SSC performance may require that movement frequency be performed in resonance with the natural frequency of the elastic structures.

Conclusions

This research has demonstrated that when untrained participants performed upper body SSC movements the natural frequency of the musculo-tendinous unit and the movement frequencies of the SSC actions were not in resonance. The failure to achieve resonance may have contributed to the unusual observation that the SSC action did not enhance concentric performance. This result supports previous research which suggested that the occurrence of resonance is an important feature of effective performance of SSC movements. The mode through which resonance occurs is an area which requires further research.

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Authors' Notes

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E-mail gwilson@scu.edu.au