Muscle Force and Activation Under Stable and Unstable Conditions

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ABSTRACT

The objective of this study was to determine differences in isometric force output, muscle activation (interpolated twitch technique), and electromyographic activity of the quadriceps, plantar flexors (PF), and their antagonists under stable and unstable conditions. Instability in subjects was introduced by making them perform contractions while seated on a "Swiss ball." Eight male subjects performed unilateral leg extensor (LE) and PF contractions while seated on a bench (LE), chair (PF), or a ball. Unstable LE and PF forces were 70.5 and 20.2% less than their stable counterparts, respectively. Unstable quadriceps and PF activation averaged 44.3 and 2.9% less than activation under stable conditions. Unstable antagonist/agonist ratios were 40.2 and 30.7% greater than stable ratios in the LE and PF protocols, respectively. The greater decrements with LE can be attributed to the instability of only 2 points of floor contact, rather than 3 points of floor contact as with the PF. Swiss balls may permit a strength training adaptation of the limbs, if instability is moderate, allowing the production of overload forces.

Key Words: balance, interpolated twitch technique, electromyography, quadriceps, plantar flexors

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Introduction

Balls have been used by entertainers and circus performers over many years. It is unclear when they first began to be used as a training and rehabilitation tool, but physical therapists have been using "Physio balls" since before World War II. With the upsurge of interest in neuromuscular training generated by researchers such as Sherrington (27, 28), physical therapists began to integrate the use of balls into therapy. Physical therapists, especially the Germans and the Swiss, were especially active in using balls for sports training and therapy. Consequently, the name "Swiss ball" has become almost synonymous with "Physio ball."

Proponents of the Swiss ball deduce that the greater instability of the ball and human body interface will stress the neuromuscular system to a greater extent than traditional resistance training methods using more stable benches and floors. The advantage of an unstable training environment would be based on the importance of neuromuscular adaptations with increases in strength. Strength gains can be attributed to both increases in muscle cross-sectional area and improvements in neuromuscular coordination (2). A number of researchers have reported that neural adaptations play the most important role in strength gains in the early portion of a resistance training program (2, 24). Rutherford and Jones (23) suggested that the specific neural adaptation occurring with training was not increased recruitment or activation of motor units, but an improved coordination of agonist, antagonists, synergists, and stabilizers. Thus, the inherently greater instability of ball and body interface would challenge the neuromuscular system to a greater extent, possibly enhancing strength gains attributed to neural adaptations.

Improvements in core stability (torso strength) have been postulated in the popular media to be enhanced with instability training. The effectiveness of Swiss ball training has been demonstrated with abdominal training. Siff (29) found that the wider range of movement (with an optimal starting position from a few degrees of active trunk extension) is preferable to similar actions performed in most circuit training gyms. However, there has been no evidence, other than anecdotal, to significantly demonstrate the overall effectiveness of Swiss ball training. Furthermore, there have been no studies documenting instability training responses on limb musculature. It is the objective of this investigation to examine the differences in force output and intramuscular and intermuscular activation of the leg extensors (LE) and plantar flexors (PF) under stable and unstable conditions.

Methods

Experimental Approach to the Problem

The same group of subjects performed isometric voluntary contractions of their knee extensors and PF un-

der stable (seated on a bench or chair) and unstable (seated on a Swiss ball) conditions. Forces derived from the maximum voluntary contractions (MVC) and muscle activation patterns were measured using the interpolated twitch technique (ITT) as well as agonist and antagonist electromyography (EMG) to discover whether unstable conditions provided similar, greater, or lesser stress on the limb musculature than while stable. All measurements have been reported to have excellent reliability and validity in the literature (5, 35, 36). In the present study, force measures illustrated excellent reliability coefficients of 0.99 for both the LE and PF. Similarly, measures of muscle inactivation with the ITT achieved reliability coefficients of 0.96 and 0.84 for the LE and PF, respectively.

Subjects

Eight physically active male subjects (24.3 ± 6.7 years, 178.1 ± 6.1 cm, 82.3 ± 8.9 kg) were recruited from the university population. Subjects were either resistance trained or had previous resistance training experience. All subjects read and signed a consent form before experimentation. The study was approved by the School of Physical Education, Recreation, and Athletics, Memorial University of Newfoundland Ethics Committee.

Testing

Subjects were given an orientation session 2–3 days before testing, which permitted them to sit on the Swiss ball and attempt as many submaximal contractions as necessary for them to feel comfortable with the apparatus. Whereas LE and PF testing were conducted on separate days, all stable and unstable testing for a particular muscle group was performed in a single session. All subjects had some experience performing sit-ups using the Swiss balls with their prior resistance training.

Leg Extensors

Subjects performed 2–3 isometric MVCs of the quadriceps. Three-minute rest periods were provided between all contractions. During the stable leg extension, subjects were seated on a bench with hips and knees at 90°, with their foot in a padded strap attached by a high tension wire to a Wheatstone bridge configuration strain gauge (Omega Engineering Inc., LCCA 250, Don Mills, Ontario, Canada), perpendicular to the lower limb. The subject's body was secured in this position with a seat belt–type apparatus across both the hips and thighs. Unstable leg extensions were performed while seated on a Swiss ball. The size of the Swiss ball was selected to ensure that the subject's floor contact leg had the knee flexed at 90°. The testing leg was secured to the padded strap and strain gauge in the same manner as in the stable condition. In the unstable LE condition, the testing leg did not touch the floor; thus there were only 2 points of balance or contact with the floor.

Plantar Flexors

Subjects in the stable condition were seated in a straight-back chair, with hips and knees at 90°. They performed voluntary contractions of the PF, with their leg secured in a modified boot apparatus, with their ankles and knees at 90° (6). Three-minute rest periods were provided between all contractions. Unstable contractions were performed with the same apparatus while seated on a Swiss ball. The modified boot apparatus rested on the floor and securely restricted the subject's leg, resulting in 3 points of balance or contact with the floor.

Measurements

All voluntary and evoked torques were detected by the strain gauges, amplified (DA 100 and analog to digital converter MP100WSW, Biopac Systems, Inc., Holliston, MA), and monitored on a computer (Sona Phoenix PC, St. John's, Newfoundland, Canada). All data were stored on a computer at a sampling rate of 2,000 Hz. Data were recorded and analyzed with a commercially designed software program (AcqKnowledge III, Biopac Systems Inc.).

Bipolar surface stimulating electrodes were secured over the proximal and distal portions of the quadriceps and PF. Stimulating electrodes, 4–5 cm in width, were constructed in the laboratory from aluminum foil and paper coated with conduction gel (Aquasonic, Fairfield, NJ) and immersed in a saline solution. The electrode length was sufficient to wrap the width of the muscle belly. The electrodes were placed in approximately the same position for each subject.

Surface EMG recording electrodes were placed approximately 3 cm apart over the midbelly of the quadriceps and hamstrings (LE protocol) and over the midbelly of the soleus and tibialis anterior (PF protocol). Ground electrodes were secured on the tibia and fibular head. Thorough skin preparation for all electrodes included removal of dead epithelial cells with an abrasive (sand) paper around the designated areas, followed by cleansing with an isopropyl alcohol swab. EMG activity was amplified, filtered (10–1,000 Hz), monitored, and stored in a computer. The computer software program rectified and integrated the EMG signal (IEMG) over a 500-millisecond period during an MVC.

The ITT was administered during an MVC for the LE protocol and both maximal and submaximal voluntary contractions for the PF protocol. An interpolated force (IT) ratio was calculated comparing the amplitudes of the superimposed stimulation with the postcontraction stimulation to estimate the extent of inactivation during a voluntary contraction (5). Because the postcontraction stimulation represents full muscle

activation, the superimposed torque using the same intensity of stimulation would activate those fibers left inactivated by the voluntary contraction. Extra or superimposed evoked force was readily apparent in the LE protocol with the ITT during an MVC. Because superimposed evoked forces could be detected during all leg extension MVCs, stimulation was provided only with maximal contractions to reduce the number of stimulations and subject discomfort. However, superimposed force during an MVC was absent in almost all subjects during the PF protocol. Thus, all maximal and submaximal (100, 75, 50, and 25% of MVC) forces were correlated with their respective IT ratios in order to generate a second-order polynomial equation for all PF subjects. Second-order polynomials using both maximal and submaximal contractions (IT ratios) have been shown to be valid and reliable, providing an accurate estimation of muscle activation (5).

Torque signals were sent through a high gain amplifier (Biopac Systems DA100 and MP100WSW), with the superimposed force isolated and further amplified by the software program (AcqKnowledge III). A doublet (2 twitches delivered at a frequency of 100 Hz) rather than a twitch was utilized for the interpolated evoked stimulation because it provided a higher signal-to-noise ratio.

Statistical Analyses

Data were analyzed with a 1-way analysis of variance with repeated measures (stable vs. unstable). F ratios were considered significant at $p \leq 0.05$. If significant interactions were present, a Bonferroni (Dunn's) procedure was conducted. Statistical power equations to determine minimum population samples to achieve significance at the $p \leq 0.05$ level with a power of 0.9 revealed that a range of 5–10 subjects was necessary, depending upon the muscle tested and measure utilized.

Results

Maximum Voluntary Contractions

The ability to exert force under stable conditions significantly exceeded force output under unstable conditions for both the LE and PF protocols. Unstable LE force was 70.5% less than stable force (Figure 1a), whereas unstable PF force was 20.2% less than stable force (Figure 1b).
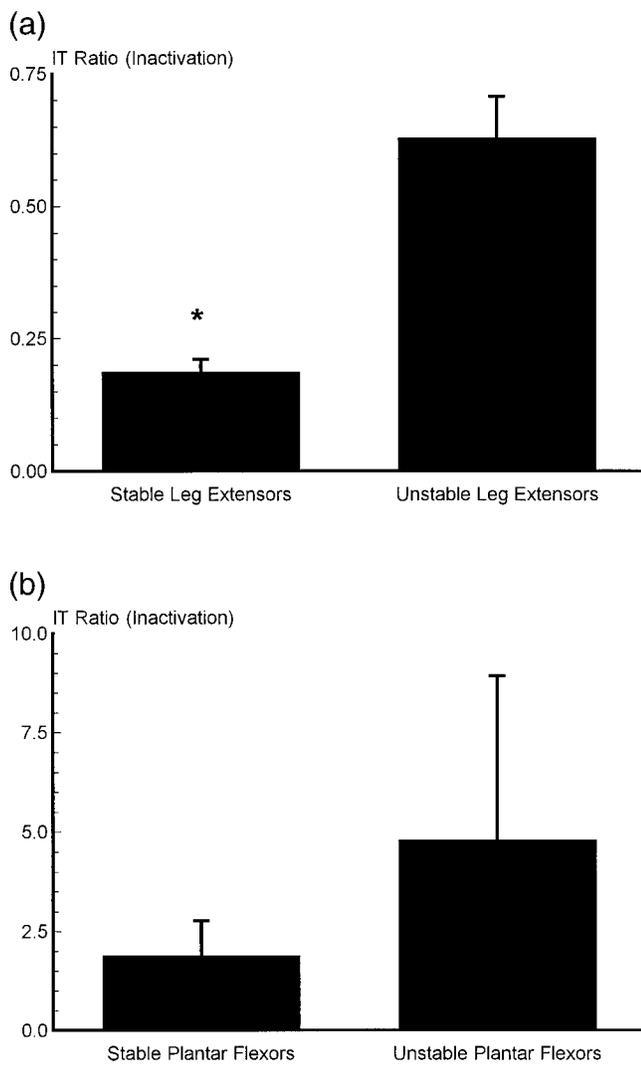
Muscle Inactivation

A significant difference in muscle inactivation was detected only with the LE protocol. Quadriceps activation under unstable conditions averaged 44.3% less than that under stable conditions (Figure 2a). Although not statistically significant, unstable PF exhibited 2.9% less activation than that under stable conditions (Figure 2b).
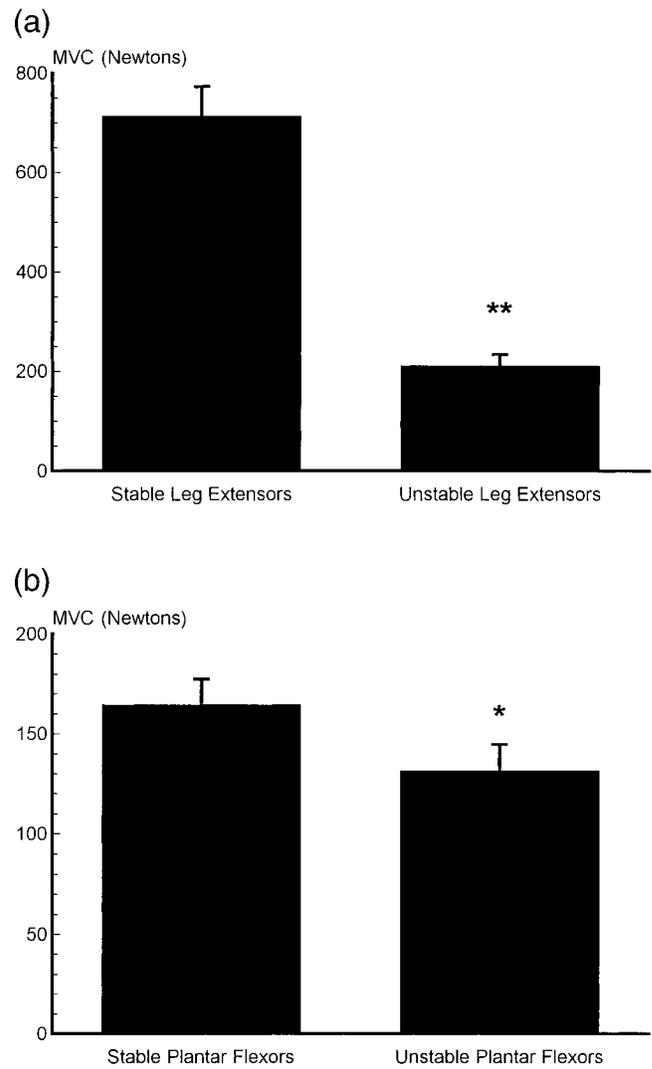
Figure 1. Bars represent changes in maximum voluntary contractions (MVC) of the leg extensors (LE) during the LE protocol (a: upper graph) and the plantar flexors (PF) during the PF protocol (b: lower graph) under stable and unstable conditions. Double asterisks indicate significant differences at the $p < 0.0001$ level, whereas single asterisks indicate significant differences at the $p < 0.01$ level. Vertical bars represent standard errors.

Antagonist and Agonist IEMG

Whereas the quadriceps experienced a dramatic decrease in activation as measured by ITT, quadriceps IEMG activity decreased only 11.3% with unstable conditions (Figure 3a). Conversely, hamstring IEMG activity increased by 29.1% under unstable vs. stable conditions (Figure 3b). Although statistically insignificant, unstable PF experienced decreases of 8.3% (Figure 4a), whereas tibialis anterior IEMG activity experienced increases of 30.3% (Figure 4b). The interaction of agonist and antagonist activity resulted in a significant difference only with the antagonist/agonist IEMG activity of the quadriceps and hamstrings. Unstable antagonist/agonist ratios were 40.2 and 30.7%
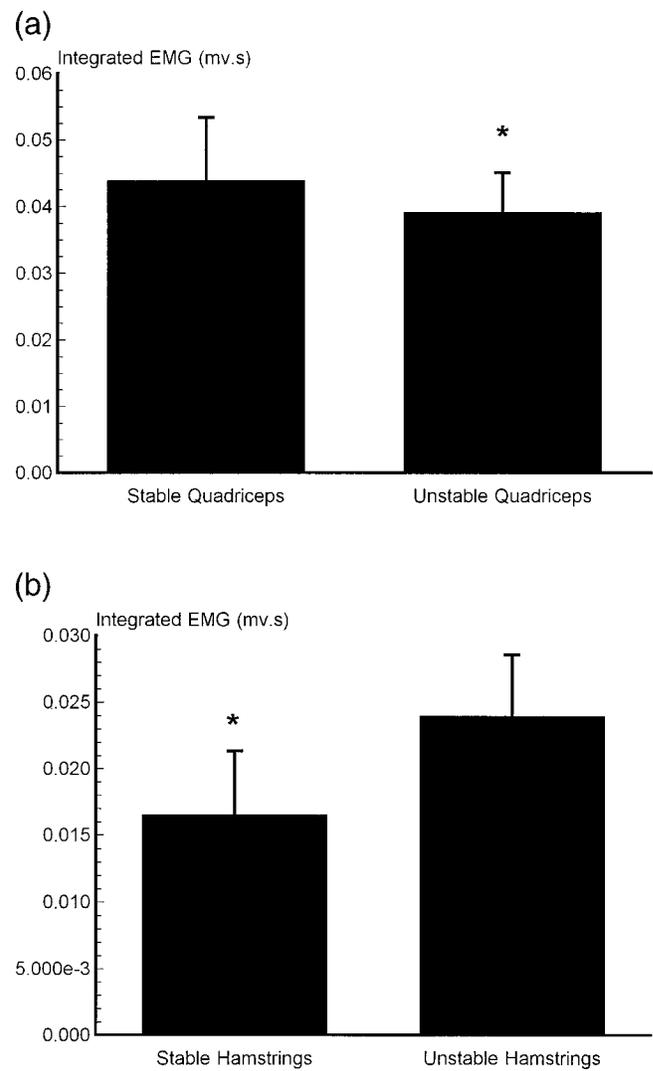
(a)

(b)

Figure 2. Bars represent changes in muscle inactivation of the leg extensors (LE) during the LE protocol (a: upper graph) and the plantar flexors (PF) during the PF protocol (b: lower graph) as estimated by the interpolated twitch technique under stable and unstable conditions. A single asterisk indicates a significant difference at the $p < 0.003$ level. Vertical bars represent standard errors.

(a)

(b)

Figure 3. Bars represent changes in agonist (quadriceps) (a: upper graph) and antagonist (hamstrings) (b: lower graph) integrated electromyography activity during the leg extensor protocol under stable and unstable conditions. A single asterisk indicates a significant difference at the $p < 0.05$ level. Vertical bars represent standard errors.

greater than stable ratios in the LE (Figure 5a) and PF ($p = 0.07$) (Figure 5b) protocols, respectively.

Discussion

This is the first paper to our knowledge to examine differences in force output and muscle activation under stable vs. unstable conditions. The proponents of training under unstable conditions with a Swiss or Physio ball claim that resistance training under unstable conditions provides a greater stress to the overall musculature. Stress, according to Selye's (26) adaptation curve, is essential in forcing the body to adapt to new stimuli. Periodization models (1, 13, 31) emphasize the importance of altering the volumes, intensities, mode, or type of exercises in order to provide novel stimuli

to the neuromuscular system. Furthermore, according to the concept of training specificity (2, 25), because not all forces are produced under stable conditions (i.e., shooting a puck while balancing on a single skate blade in hockey, performing a routine on a balance beam, and changing direction rapidly by pivoting on 1 foot on uneven natural turf in football, soccer, field hockey, or other sports), training must attempt to closely mimic the demands of the sport or occupation. There is an infinite array of exercises that can be performed on the Swiss ball for both the upper and lower body. Whereas some exercises stress the knee extensors and flexors by rolling forward and backward on a stability ball, with the body used as load, other practitioners perform feats of balance involving unassisted squats on a freely moving ball. Whether some of these
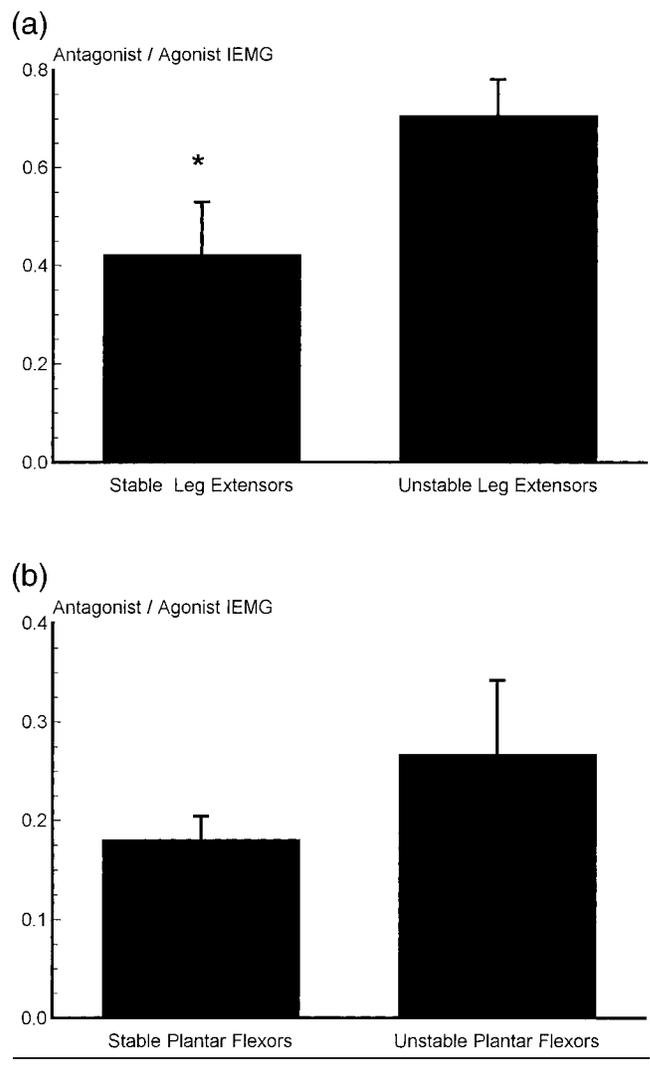
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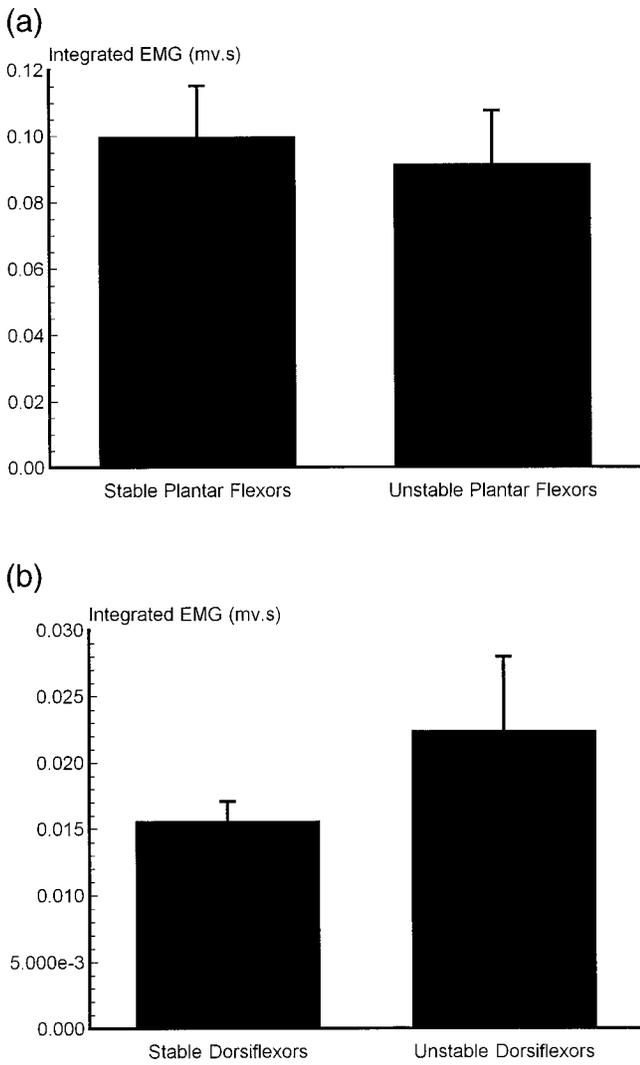
Figure 4. Bars represent changes in agonist (plantar flexors [PF]) (a: upper graph) and antagonist (tibialis anterior) (b: lower graph) integrated electromyography activity during the PF protocol under stable and unstable conditions.

Figure 5. Bars represent changes in antagonist/agonist ratio of the leg extensors (a: upper graph) and plantar flexors (b: lower graph) under stable and unstable conditions. A single asterisk indicates a significant difference at the $p < 0.05$ level. Vertical bars represent standard errors.

circus-style maneuvers provide specific crossover training adaptations to sport is still under debate and demands further investigation.

Some authors advise the use of free weights over machines for improved training results (30) because the balance and control of free weights forces the individual to stress and coordinate more synergist, stabilizing, and antagonist muscle groups. The rationale underlying destabilizing training environments would lead one to conclude that unstable environments should provide a more varied and effective training stimulus.

Force outputs with both LE and PF protocols were significantly lower with unstable conditions than with stable conditions. There was a much greater decrease in force with the unstable LE (70.5%) than PF (20.2%) as compared with their stable counterparts. This can be attributed to the differing degrees of instability in

the 2 protocols. The LE setup provided only 2 points of contact with the floor (ball and contralateral limb on floor), whereas the PF protocol had 3 points of contact (ball, contralateral limb on floor, and testing limb in stable boot apparatus). Because there appeared to be a hierarchy of force output, with stable conditions providing the greatest forces, moderately unstable (PF) forces affected significantly, and very unstable (LE) conditions affected severely, the degree of stability or instability seems to directly affect limb force production. On one hand, this might promote the essential point of instability training; that is, because forces have been demonstrated to be lower with unstable conditions, training in that environment is of utmost necessity to ensure action-specific strength adaptations. Conversely, overload tension on the muscle is essential for fostering strength training adaptations (2, 33). Force output with unstable LE was only 29.5% of

a stable MVC. A number of authors have stated that training programs to promote general and maximal strength need repetitions, which provide a resistance intensity in the range of 40–120% of 1 repetition maximum or MVC (17, 30, 33). A very unstable environment, as provided in the present LE protocol, would not provide sufficient overload resistance (29.5%) to promote quadriceps strength adaptations. Although the PF protocol also had significantly less force than the stable condition, the degree or intensity of the contraction could still supply an overload stress (79.8% of stable MVC) on the muscle, with a limited number of contractions. Although forces and muscle activity of the torso were not measured in the present study, it may be possible that the torso musculature received an overload stress in attempting to maintain equilibrium.

Similar to force results, muscle inactivation experienced the greatest decrements under the very unstable LE condition (62.9%). Whereas some researchers have demonstrated full activation of the quadriceps under stable conditions (7, 8, 10, 22), others have reported less than full activation (5, 9, 15, 20, 32). The decreased activation under very unstable conditions could be ascribed to the excess stress associated with the increased postural demands (12). It could also be related to the dispersion of concentration (neural drive) in attempting to control 2 limbs with differing responsibilities (balance and force) (34). In an attempt to maintain balance, synergistic and stabilizing muscles would play a greater role. Synergistic muscles have been shown to provide both inhibitory and facilitatory inputs to agonist muscle groups (21). Thus, the application of 2 major stressors to the central nervous system (attempting maximal force output while balancing on 2 points) in this study severely inhibited the ability to fully activate the quadriceps.

However, the activation of the PF, which experienced only a moderately unstable condition, was not significantly affected. Unstable PF activation was only 2.9% lower than stable PF activation. However, it must be emphasized that the PF condition had 3 points of contact, minimizing the stress on the equilibrium system. Secondly, the PF may be more amenable to complete activation in many individuals. Stable PF inactivation (1.8%) was significantly less than stable LE inactivation (18.6%). Under stable conditions, both McComas et al. (19) and Belanger and McComas (6) reported that half their subjects could fully activate their PF. Similarly, Behm and St-Pierre in 2 separate studies indicated that 10 of 12 (3) and 11 of 16 (4) subjects could fully activate their PF during stable conditions. Because the PF posed a minimal challenge to the equilibrium of the body, may be accustomed to more chronic postural demands, and is a smaller muscle group than the quadriceps, which may be easier to fully activate, insignificant changes were experienced under this condition.

A question then arises as to why unstable PF forces were significantly less than stable PF forces, when there was no significant difference in muscle activation. Although not statistically significant, there was a trend ($p = 0.07$) for a greater antagonist/agonist ratio with the unstable PF condition. The unstable PF condition experienced 30.7% greater antagonist activity than the stable PF condition. Similarly, but in this instance statistically significant, unstable LE experienced 40.2% greater antagonist activity. The role of the antagonist in this case may be an attempt to control the position of the limb when producing force. Both De Luca and Mambrito (11) and Marsden et al. (18) reported that antagonist activity was greater when uncertainty existed in the required task. Increased antagonist activity may also be present to increase joint stiffness (16) to promote stability (14). Whereas increased antagonist activity could be utilized to improve motor control and balance, it would also contribute to a greater decrement in force with the unstable conditions.

Practical Applications

Unstable conditions can lead to decreases in the force output of the limb, muscle activation, and increases in antagonist activity. Greater degrees of instability exacerbate these changes. In the light of these findings, the use of Swiss or Physio balls as a resistance training modality for peripheral strength gains should be employed when the degree of instability is light to moderate, allowing an overload force or resistance to be developed. For example, if an individual is in a position whereby he or she cannot stay upright (attempting to stand or perform a squat maneuver on a Swiss ball), the amount of resistance that can be applied to the muscle will be negligible because all focus is on balance (extreme instability). On the other hand, performing contractions while seated on a Swiss ball, with 1 or 2 feet on the floor (moderate-to-light instability), requires less focus to maintain balance, and hence more concentration and resources can be applied to moving greater resistances. However, whereas the resistive challenge to a limb under very unstable conditions may be less than that necessary to develop strength adaptations, the torso musculature may be under greater stress. With unstable conditions, a relatively small resistive torque on the distal portion of a limb can result in substantial motive torque by the torso. Perhaps, the greatest contribution of instability training may be to improve core stability rather than limb strength. In addition, the preliminary purpose of the stability ball need not be significant strength gains but an attempt to improve balance, stability, and proprioceptive capabilities. Further research is necessary

to investigate the effects of instability training on torso strength and balance adaptations as well as the effectiveness of a prolonged resistance training program using both unstable and stable conditions.

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