Force Irregularity Following Maximal Effort: The After-Peak Reduction

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Abstract
Irregularities in force output are present throughout human movement and can impair task performance. We investigated the presence of a large force discontinuity (after-peak reduction, APR) that appeared immediately following peak in maximal effort ramp contractions performed with the thumb adductor and ankle dorsiflexor muscles in 25 young adult participants (76% males, 24% females; M age 24.4 years, $SD = 7.1$). The after-peak reduction displayed similar parameters in both muscle groups with comparable drops in force during the after-peak reduction minima (thumb adductor: $27.5 \pm 7.5\%$ maximal voluntary contraction; ankle dorsiflexor: $25.8 \pm 6.2\%$ maximal voluntary contraction). A trend for the presence of fewer after-peak reductions with successive ramp trials was observed, suggesting a learning effect. Further investigation should explore underlying neural mechanisms contributing to the after-peak reduction.

Keywords
force variability, motor control, force output, fine motor coordination, gross motor coordination

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Introduction

The human motor system is capable of performing a vast repertoire of skilled movements. Within this diversity of motor action is the ability not only to maintain muscular forces at constant levels when necessary but also to modulate force production precisely when needed. Accurate gradation of force in the hand is important for daily living skills (Marshall & Armstrong, 2004). Tasks such as eating, writing, and manipulating electronic devices require a delicate fingertip precision grip; carrying objects, cooking, lifting, and transporting items often involve use of a power grip where maximal force contractions are needed (Long, Conrad, Hall, & Furler, 1970). Similarly, force regulation in the lower extremity must be precisely coordinated to maintain balance to prevent falls (King, Stylianou, Kluding, Jernigan & Luchies, 2012) or to ambulate functionally (Noble & Prentice, 2006). In normal healthy individuals, tactile feedback from the periphery allows accurate prediction and adjustment of forces needed for successful movements (for review, see Johansson & Flanagan, 2009).

Precise force gradation involves coordinated agonist and antagonist activity; weakness, fatigue, or neurological insults that alter this balance can create force irregularity, variability, and ultimately impair task performance. Discontinuities in force output have been identified during constant load isometric contractions of individual finger musculature (Taylor, Christou, & Enoka, 2003), during pinching tasks (Vaillancourt, Slifkin, & Newell, 2002) and also in larger lower extremity muscles (Christou & Carlton, 2002; Tracy, Byrnes, & Enoka, 2004). Force fluctuations also tend to increase with intensity of contraction during constant-force isometric contractions (Oshita & Yano, 2010, 2011; Slifkin & Newell, 1999).

Gradually decreasing force output from maximal effort to a lower force during a motor task can also create discontinuities within the movement. Greater accuracy deficits were seen during the force decrease phase of a sub-maximal pinching task when compared to the force increase phase in elderly individuals (Francis, MacRae, Spirduso, & Eakin, 2012; Spirduso & Choi, 1992). Similarly, participants showed greater force variability during release of force as compared to the force increase phase during a visual-matching task with the index finger (Masumoto & Inui, 2011). Because force is suggested to be more variable at greater intensities, and the release of maximal forces generates irregularities in force output, the study of force variability during release of maximal effort is warranted. Previous studies, however, have not fully examined force fluctuations occurring following a graded decrease from maximal effort.

The initial purpose of this study was to investigate and describe force variability during visually guided ramp contractions of ankle dorsiflexion (ADF) in young healthy adults. In the process, we observed the presence of a distinct, large force fluctuation seen repeatedly following attainment of maximal force, which we termed as the after-peak reduction (APR). The APR presented as a rapid, large drop in force immediately after reaching peak force followed by a sudden recovery to the target force trajectory. The purpose of this study

was to examine and characterize the APR further, determine if this anomaly was present in both large and small muscle groups, and to determine if the frequency of the APR changed over subsequent trials. To do so, we used a visually guided isometric ramp contraction that began at the zero force baseline and slowly increased to 100% maximal voluntary contraction (MVC) at the peak then slowly decreased back to return to baseline (Figure 1). We analyzed landmark components of the APR (onset and minima), compared the force output from ADF ramps to similar visually guided ramp contractions of thumb adduction, and evaluated whether the occurrence of the APR decreased with the performance of successive ramp contractions.

The hypotheses were (1) that the APR would be present across participants and appear in both large and small muscle groups as the movements were biomechanically comparable and similarly modulated through the human neuromuscular system; and (2) that there would be a learning effect by which participants could reduce the amplitude of the APR or eliminate the behavior altogether (thereby increasing the accuracy in matching the target trajectory) with subsequent trials.

Method

Participants

Twenty-five healthy adult volunteers (19 males, 6 females) aged 18–44 years participated in this study. Participants were not athletically trained and were
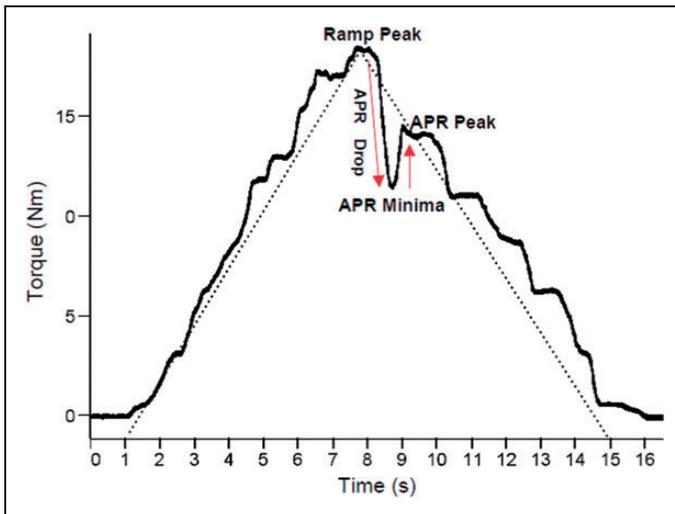
Figure 1. Representative force-time plot for one isometric ramp contraction. APR showing landmarks used in analysis. Ramp peak, APR drop, APR minima, and APR peak are noted. Arrows indicate the force decline from ramp peak to minima of APR, and subsequent force increase from minima of APR back toward APR peak and original ramp trajectory.

free of injury to the limb that was tested. Participants were divided into the ADF group ($n = 16$) and the thumb adduction group ($n = 9$). The initial investigation focused on analysis of force variability in the ADF muscle during ramp contractions; however, when the APR was observed, a thumb adduction group was added to determine if similar patterns of force control were also present in fine motor muscles of the hand. Participants reported no musculoskeletal or neurological impairment. Experimental procedures were approved by the university Institutional Review Board and all participants signed individual consent forms.

Materials and procedure

For the thumb adduction task, nine participants (four males, five females) were seated in a high-back chair with their left forearm pronated and immobilized in a custom-designed splint made of thermoplastic material. The shoulder and upper arm were positioned parallel with the trunk and the elbow was positioned at 90° of flexion. Straps at the wrist, forearm, upper arm, and shoulder secured limb and hand position. Therapeutic hand putty secured the phalanges; a small thermoplastic plate was placed on top of the putty and secured with a Velcro strap to maintain hand position. Visual display of the force was provided on a computer monitor positioned in front of the participant. The palmar surface of the thumb of the non-dominant hand was positioned against a force transducer that measured thumb adduction force. The non-dominant hand was selected for study to eliminate confounding that might occur due to individual differences in dominant hand use. Participants were instructed to apply a parallel adduction force to the metal strain gauge at the interphalangeal joint of the thumb and to avoid flexing the interphalangeal joint and the distal phalanx of the thumb. Surface electromyographical (EMG) data were collected through active and reference electrodes placed over the palmar surface of the adductor pollicis muscle. A ground electrode was placed over the pisiform bone.

For the ADF task, 16 (15 males, 1 female) participants were seated in an adjustable chair and positioned in 90° of hip and knee flexion with the ankle positioned in neutral. All participants used the right leg to perform an isometric contraction with the ankle dorsiflexor muscles. The knee and ankle joints were immobilized with a padded clamp positioned proximal to the knee joint. The foot was strapped across the forefoot to an aluminum plate fitted with a strain gauge to measure ankle force. Bipolar Ag-AgCl electromyographic recording electrodes with preamplifiers were placed over the belly of the tibialis anterior muscle. A ground electrode was placed between the recording electrodes and the tibial tuberosity.

First, three MVCs of thumb adduction or ADF were performed. Three MVCs are commonly used to determine performance of MVC (Mettler & Griffin, 2012; Vaillancourt et al., 2002). The participants then performed five isometric ramp contractions of thumb adduction or ADF from rest to MVC and back to rest. Each trial was separated by 5 seconds of rest. Five trials were used to compare and stabilize motor performance and to examine practice effects.

The ramp trajectory was an inverted "V" pattern that began at the zero force baseline, increased to 100% MVC at the peak, then decreased back to return to baseline (Figure 1).

Participants were instructed to match force output as closely as possible to the target line of the ramp trajectory template displayed on the computer monitor by gradually increasing force from rest to MVC, and then gradually decreasing force back to rest. The ramped trajectory spanned 10 seconds for the thumb adduction group (5 seconds from baseline to peak and 5 seconds from peak back to baseline) and spanned 15 seconds for the ADF group (7.5 seconds from baseline to peak and 7.5 seconds from peak back to baseline). Ramp time was slightly extended for the ADF task as eye-hand reaction times have been found to be faster when compared to eye-foot reaction times in visually normal individuals (Gould, Ciuffreda, Yadav, Thiagarajan, & Arthur, 2013).

Data collection and analysis

For the ADF task, the analog force signal from the strain gauge was amplified (Vetter digital PCM), digitally converted (CED expansion ADC12 MICRO 1401), and low-pass filtered at 100 Hz. Surface EMG data were bandpass filtered at 5–1000 Hz and sampled at 2000 Hz. For the thumb adduction task, analog force data were amplified (Bridge 8 Amplifier System, Model 74030, World Precision Instruments, Sarasota, FL), digitally converted at 2000 Hz, and low-pass filtered at 1 kHz. Surface EMG was amplified and high-pass filtered above 8 Hz (Coulbourn Instruments, Allentown, PA) and also sampled at 2000 Hz. All data were recorded and analyzed off-line using Spike 2 software (v. 5, CED, Cambridge, Cambridge, UK).

The EMG signal was full-wave rectified and normalized to ramp peak and time. EMG data were analyzed by dividing each ramp into two phases. The first phase, the force increase phase, was defined as the time from onset of muscle activity to peak EMG. The second phase, the force decrease phase, was defined as the time immediately following peak EMG to termination of muscle activity. Figure 2 displays the EMG from one ramp contraction of the tibialis anterior muscle.

The APR was defined as a distinctly larger force fluctuation seen regularly following attainment of peak force in the force decrease phase. The unique pattern included a rapid, nearly instantaneous drop in force immediately after reaching peak force followed by a sudden recovery to the target force trajectory. All force fluctuations occurring immediately after peak force were recorded and the irregularity was classified as an APR if the reduction in force (defined as the APR drop) was $\geq 10\%$ of MVC. This value was selected as it represented a visible change that was consistent in both the recorded signal and the EMG force trace, and the 10% MVC drop distinctly differed from the other observed force fluctuations. Figure 1 displays the ramp peak, APR drop, APR minima, and APR peak landmarks in a representative ramp. Figure 2 displays the
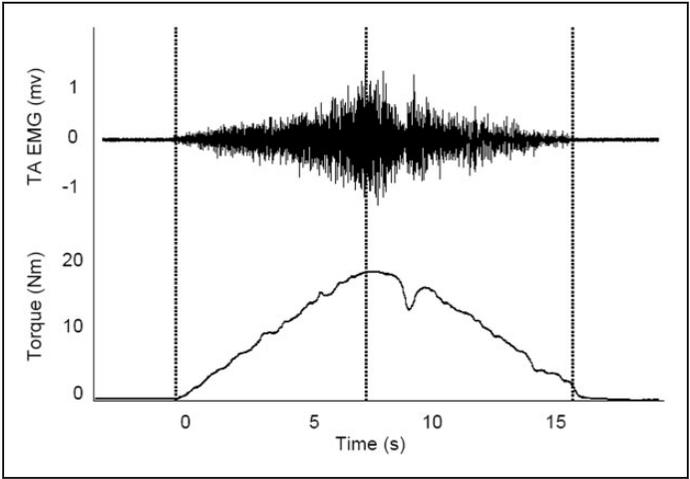
Figure 2. Surface EMG (top trace) and force (bottom trace) during typical ramp contraction. EMG activity during minima of APR is markedly reduced. Dotted lines indicate initiation of EMG, peak of EMG, and return to baseline.

resultant APR through the EMG signal. We described the APR phenomenon by calculating the number of ramps that exhibited an APR and assessed changes in the frequency of the APR over successive trials. We also measured the percent of MVC during the force decrease phase of the guided ramp contraction at which the APR drop began (APR onset) and the percent of MVC that the force level dropped to minima (lowest point) during the APR. The APR peak is the point at which force returned to approximate the target line following the APR minima.

Statistical analysis

Because we were interested in whether the APR presented similarly in the ADF and thumb adductor tasks, we used one-way analysis of variance (ANOVA) to compare the percentage of ramps with the APR and the drop to minima values between the two groups. The APR onset data did not meet normality criteria; therefore, a Kruskal–Wallis one-way ANOVA on ranks was performed. To examine whether the frequency of APRs changed across the five successive ramps performed in the two muscle groups, a two-way repeated measures ANOVA (group × ramp number) was used. Differences in EMG area during ramp increase and decrease phases were also compared using a Kruskal–Wallis one-way ANOVA on ranks. An alpha level of .05 was used for all statistical comparisons and significance accepted when $p < .05$. All data are presented as mean ± standard deviation throughout the text and mean ± standard error of the mean for the tables and figures.

Table 1. After peak reduction (APR) data.

Muscle group	% Ramps w/ APR	APR onset (% MVC)	APR drop to minima (% MVC)
Thumb adductor	66.67 ± 11.06	96.64 ± 1.02	27.50 ± 2.63
Ankle dorsiflexor	52.5 ± 4.43	92.41 ± 1.49	25.83 ± 1.54
p	.17	.03*	0.22

MVC: maximal voluntary contractions.
*$p < .05$.

Results

The mean MVC force was 2.88 ± 1.02 Nm for the thumb adduction task and 26.20 ± 1.27 Nm for the ADF task. Table 1 shows the percentage of ramps exhibiting the APR in each muscle group and the force level (% MVC) at which the APR onset occurred following ramp peak (where force was at 100% MVC), the force level (% MVC) at which the APR onset occurred. The APR drops to minima, expressed as the percentage of the MVC value that the force dropped when it reached the lowest point of the APR, are also shown in Table 1. Both muscle groups showed a similar percentage of ramps exhibiting the APR with no significant differences between group averages.

A significant difference was found between the ADF and thumb adduction groups for APR onset ($H = 4.76$, $p < .05$). The one-way ANOVA for the APR drop to minima values in the two groups showed no significant difference, $F(1, 24) = 1.59$, $p > .05$. Average EMG area for both muscle groups in the ascending phase ($1.09 \pm 0.002\%$ peak EMG/s) was significantly greater ($H = 11.67$, $p < .05$) when compared to average EMG area in the descending phase ($0.73 \pm 0.002\%$ peak EMG/s).

In the five ramps performed by each participant, the number of APRs ranged from a minimum of zero in five ramps (0%) to a maximum of five in five ramps (100%) per participant (thumb adduction $M = 3.3 \pm 1.66$ APRs; ADF $M = 2.75 \pm 0.77$ APRs). The percent of ramps with an APR was calculated for each ramp number individually and for each muscle group. The percentages of APRs observed in each of the five ramps for the two groups are shown in Figure 3.

Although ramp 1 consistently showed the greatest number of APR occurrences in both muscle groups, APRs continued to appear in subsequent ramp trials. In the thumb adduction group, 23.3% of all APRs recorded occurred in the first ramp with the number of APRs decreasing as subsequent ramps were performed (20.0% in the second, third, and fifth ramps; 16.6% in fourth ramps). In the ADF group, 33.3% of all APRs were present in the first ramps, 19.0% in the second ramps, 14.3% in the third ramps, and 16.7% in the fourth and final ramps. Although the two-way ANOVA results indicated that there was not
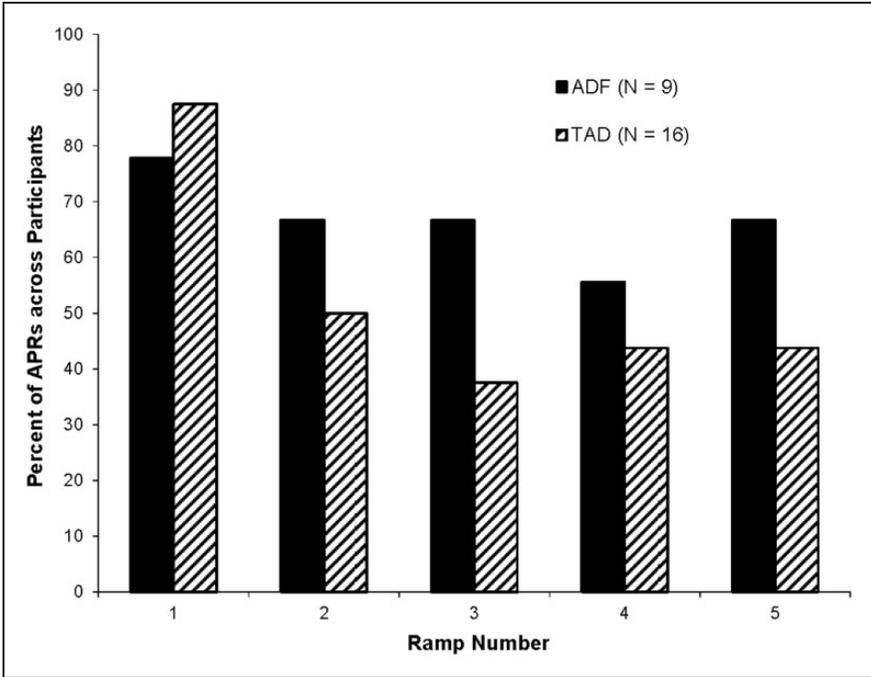
Figure 3. The percent of APRs across all participants for each muscle group is plotted for each successive ramp contraction performed. ADF = Ankle dorsiflexion; TAD = Thumb adduction.

a significant change in number of APRs across successive ramp contractions, $F(1, 24)$, $p > .05$, we did observe a trend for the presence of fewer APRs with successive ramp trials (Figure 3). No interaction effect was found.

Discussion

Successful outcomes of motor tasks are dependent on movement accuracy. Force variability and decreased motor control were observed in the thumb adduction and ankle dorsiflexor tasks immediately after maximal peak force during isometric ramp contractions. This study is the first to define and describe the presence of the APR, a phenomenon repeatedly occurring in ramp contractions to maximal effort performed with both large and small muscle groups.

Over half of all ramps performed exhibited the presence of an APR. The APR displayed common components despite occurring in physiologically and functionally dissimilar muscles. Increased variability of force output has been previously observed in the hand during ramp contractions (Lindberg, Ody, Feydy & Maier, 2009) and during visually guided force tracking tasks when targets

require participants to produce force increases and decreases in sinusoidal or ramp-like contractions (Keogh, Morrison, & Barrett, 2007; Voelcker-Rehage & Alberts, 2007). Similar force variability was seen in the ankles of older adults who performed a sinusoidal tracking task using dorsi- and plantarflexion as a measure of driving ability (Lodha, Moon, Kim, Onushko, & Christou, 2016). Attempts at decreasing force following a maximal contraction in our experimental task yielded the same uncontrolled response of the APR in the hand as well as the ankle. These findings suggest that the physiological mechanisms that produce the APR may be present in both large and small fine motor skill muscle groups during attempts at graded decreases of maximal isometric force.

The number of APRs gradually decreased across the first four ramps performed in the thumb adduction task and the first three ramps performed in the ADF task. If the APR is classified as a movement error, motor learning literature reinforces the tenet that errors decrease with increased practice and a learning effect occurs (Schmidt & Lee, 2005, p. 305); therefore, the initial decrease in consecutive APRs would be expected. However, APRs still persisted in later ramps suggesting that a component of the APR may be resistant to learning or that voluntary adaptive efforts to more closely approximate the target line were difficult. Adaptive corrections to a movement trajectory are continually monitored using feedback and feedforward control that allows for adjustment of limb position and speed to meet the demands of the task (Lackner & Dizio, 1994; Seidler, Kwak, Fling, & Bernard, 2013).

The external visual feedback, as was present in this study, has been shown to influence motor performance at a systems level. Slifkin, Vaillancourt, and Newell (2000) found that when subjects were required to maintain a steady, constant force using the index finger, visual processing occurred at a much higher frequency (6.4 Hz) than the resulting motor output for error correction (1 Hz). This suggests that although movement errors are visually recognized and processed rapidly, the motor response needed to correct the movement error is significantly slower. Thus, it is possible that visual feedback could have been used for error correction and that the APR represents the delayed voluntary activation used to reapproximate the visual target line when the force produced fell above or below the intended level. Similarly, visual feedback of a force trace contributed to variations in force output in the dorsiflexor muscles of the ankle during performance of constant submaximal contractions; Tracy (2007) attributed this to attempts at error correction while multiple afferent information (visual, limb, and proprioceptive) is being processed simultaneously. Future work determining whether an APR can be cognitively or motorically controlled or prevented would contribute to understanding the APR behavior in more detail.

Additionally, tactile awareness communicated by pressure receptors in the foot and the thumb are dynamically changing throughout the performance of a force-matching isometric task. Skin mechanoreceptors and the associated slow-conducting Type C fibers are responsive to and capable of communicating

joint position in response to skin stretch (Edin, 2001). As force is decreased following the peak, pressure receptors are being unloaded, gradually losing the skin–object interface needed for appropriate haptic feedback. The transition from the high-intensity force with maximal somatosensory feedback needed in the increase phase to the finely graded release from maximal effort needed in the decrease phase could result in an inaccurate and inordinate release of force. The reduction of this sensory input following maximal effort should contribute to difficulty in controlling force release and to the sudden drop in force seen in the APR. As can be seen in Figure 2, the EMG signal was interrupted and showed a notable decrease in output at about the time of APR onset. The presence of the APR in the force decrease phase created an asymmetrical signal modulation that resulted in significant differences in signal output between the ramp increase and decrease phases.

Although our findings that the APR onset occurred at similar time periods during the force decrease phase in the ankle dorsiflexor and thumb adductor muscles, the drop to minima was similar across both muscle groups. This suggests that a central mechanism or process for force correction may be exerted on the motor output. Fluctuations during force production have been previously and extensively identified in the literature. Terminology describing these fluctuations varies, including "pulsatile motor output" (Wessberg & Kakuda, 1999), "intermittent motor control" and "pulsatile velocity changes" (Gross et al., 2002), "movement discontinuities" (Vallbo & Wessberg, 1993), and more generally, "motor output variability" (Laidlaw, Hunter, & Enoka, 2002). In their review of motor variability, Bays and Wolpert (2007) reinforce that performance of an optimal desired visual trajectory depends on limb dynamics and the influence of the surrounding environment.

The precise physiological and biochemical mechanisms that may be contributing to the APR are unclear and warrant appropriate investigation. Possible sources for this motor anomaly could be the presence of persistent inward currents or muscle thixotropy. Persistent inward currents of calcium ions have been found in mammalian neural cells (Powers & Binder, 2001). These currents occur at voltage-sensitive calcium channels on the proximal and distal portions of the motor neuron dendrites and can have considerable effects on motor unit firing rates (Heckman, Lee, & Brownstone, 2003). Persistent inward currents have been associated with plateau potentials in motoneurons and self-sustained firing of single motor units in humans, whereby motor unit discharge is sustained despite reduction or removal of stimulation (Gorassini, Bennett, & Yang, 1998; Kiehn & Eken, 1997). During a maximal isometric contraction, when most motor units are discharging at a high rate, persistent inward currents may contribute to the continued motor unit discharge that could result in force discontinuities at this transition point. Thixotropy, another possible contributor to the APR, is a phenomenon present in extrafusal and intrafusal muscle fibers whereby a level of muscular tension remains following a muscle contraction

from residual actin–myosin cross bridge formation. This can cause unpredictable muscle tension during movement (for review, see Proske, Morgan, & Gregory, 1993). Tension persisting after maximal force due to thixotropic effects could impair feedback for accurate and graded release of force. Thixotropic properties have been well documented in the muscle spindle system, whereby "sensory after-effects" appear following forceful isometric or non-isometric muscle activity (Hagbarth & Nordin, 1998; Ishihara, Izumizaki, Atsumi, & Homma, 2004; Tsay, Savage, Allen, & Proske, 2014; Yasuda et al., 2006).

Limitations to the study include a relatively small participant number and lack of control group. In order to accurately determine the precise mechanisms that may contribute to the APR, more comprehensive methods are required which were beyond the scope of this initial study.

Because the thumb adductor group was added after the ADF group analysis was completed, we used between-subject statistical comparisons which can increase inter-subject variability. It is possible that within-subject comparisons would have resulted in more differences between muscle groups and should be used in future studies.

Conclusions

No investigation to date has identified the distinct event of the large force irregularity following maximal effort that we have termed the APR. The decrease from peak force during ramp contractions when following a visual target line appears to be a challenging motor control issue in both large and small muscle groups as evidenced by the consistent appearance of the APR. These findings are important for tasks where accuracy of motor control and precision movement are required. Further study with more comprehensive analysis is warranted to determine the effect the APR may have on functional performance of motor tasks, and whether this motor behavior can be modified with training or specific learning strategies. Additionally, more investigation should be undertaken to ascertain whether this force anomaly is also present following ramp contractions to submaximal levels. As important, probable biochemical and mechanistic variables contributing to this activity should be further explored as well.

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