Heaviness Perception Dynamics in the Leg and Arm

by

Morgan Waddell

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Graduate Supervisory Committee:

Eric Amazeen, Chair
Polemnia Amazeen
Gene Brewer

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ABSTRACT

Perceived heaviness of lifted objects has been shown to scale to a ratio of muscle activity and movement during elbow lifts. This scaling reflects the importance of the forces applied to an object and the resulting kinematics for this perception. The current study determined whether these perceived heaviness dynamics are similar in other lifting conditions. Anatomically sourced context-conditioned variability has implications for motor control. The current study investigated whether these implications also hold for heaviness perception. In two experiments participants lifted objects with knee extension lifts and with several arm lifts and reported perceived heaviness. The resulting psychophysiological functions revealed the hypothesized muscle activity and movement ratio in both leg and arms lifts. Further, principal component regressions showed that the forearm flexors and corresponding joint angular accelerations were most relevant for perceived heaviness during arm lifts. Perceived heaviness dynamics are similar in the arms and legs.

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INTRODUCTION

Weight perception is a function of muscular activity and lifting kinematics. Until recently, these variables and their contributions to perceived heaviness were investigated separately. These studies have shown that muscle activity can relate linearly and nonlinearly to perception of effort and heaviness (Hagberg, 1981; De Morree, Klein, & Marcora, 2012, Lippold, 1952). Investigations of movement in weight perception demonstrated that as apparent acceleration of an object increased its perceived heaviness decreased (Streit, Shockley, Morris, & Riley, 2007; Streit, Shockley, & Riley, 2007). Investigation of these influences in combination yielded accurate predictions of the perceived heaviness of lifted objects (Waddell, Fine, Likens, Amazeen, & Amazeen, 2016). This proposed combination reflected the dynamics of heaviness perception in unilateral elbow flexion lifts. Its ability to describe these dynamics should be investigated across other lifting conditions. The goal of the proposed studies is to gain a more complete understanding of how the body and environment interact for perception by extending this hypothesis to other muscles and lifting movements.

Muscles and Movement

Muscle contractions result from an increasing recruitment and firing rate of motor units (Kamen & Caldwell, 1996; Milner-Brown, & Stein, 1975). The summed extracellular currents from several motor units active during a muscle contraction compose the EMG signal which can be recorded with electromyography. By measuring the EMG signal along with perceptual reports of perceived effort and heaviness, previous research has shown that the perceived weight of an object is a function of muscle activity.

In these studies EMG increased with the mass of held objects along with subjective ratings of perceived effort and heaviness (Hagberg, 1981; De Moree, Klein & Marcora, 2012). The EMG signal from participants who performed shoulder forward flexion movements with handheld weights increased as the mass of the handheld weights increased (Hagberg, 1981). The EMG from these movements also correlated with measures of load, torque, and perceived exertion (Hagberg, 1981). De Morree el al., (2012) similarly investigated how EMG and perceived effort related to the mass of lifted objects. EMG, perceived effort, and movement-related cortical potential (MRCP) correlated with the mass of the lifted weights. These findings show that muscle activity was related not only to the mass of an object being manipulated, but also to the subjective experience of lifting that object.

Kinematics from manipulating an object also influence perceived heaviness (Streit, Shockley, Morris, & Riley, 2007; Streit, Shockley, & Riley, 2007). Participants wielded hidden rods and reported perceived heaviness while viewing virtual representations of their movements on a screen. Manipulating the angular acceleration of the virtual movements influenced perceived heaviness. Increasing the angular acceleration led to lower ratings of heaviness and decreasing the angular acceleration led to higher ratings – rods that appeared to move slower felt heavier than rods that appeared to move faster. Newton's second law of motion: the force required to move an object is equal to the object's mass times its acceleration, predicts this finding. In this relationship, changing the apparent acceleration will change the perceived heaviness of the object. Newton's second law tells us that in order to know the mass of a wielded object we must know both the force we are using to move it and its acceleration. All of this suggests that muscle activity and movement should be studied together.

In the research mentioned so far, EMG and acceleration's contributions to perceived heaviness were studied separately. Waddell et al. (2016) identified a proximal mechanism for weight perception that combined muscle activity and resulting lifting movements by recording EMG, acceleration, and perceived heaviness. Participants lifted objects that varied in mass and volume while the EMG signal from the biceps brachii muscle was recorded. Angular acceleration was also recorded while participants lifted the objects with unilateral elbow flexion lifts. Results showed that perceived heaviness scaled to a ratio of EMG to angular acceleration in the following psychophysiological power function:

$$Perceived\ Heaviness = 10^{0.38}\frac{EMG^{0.86}}{Acceleration^{0.65}} \qquad (1).$$

This showed that perceived heaviness was not a function of forces or acceleration separately. Instead, EMG as a proxy for force, and acceleration combined may be sensitive to weight perception. As seen in equation 1, force and acceleration combined in a way similar to Newton's second law. Both the force used and acceleration of an object combined to allowed participants to perceive the mass (heaviness) of an object. We use our bodies and our action to perceive.

Perceived Heaviness and the Inertia Tensor

In the size-weight illusion, objects with the same mass but different volumes have different perceived heaviness. The larger object feels lighter that the smaller object (Amazeen & Turvey 1996, Stevens and Rubin 1970, Dresslar, 1894). This illusion necessitated identifying a property other than mass as the stimulus for heaviness perception. Several studies investigated stimulus properties such as shape (Dresslar, 1894) and density (Harshfield & DeHardt, 1970; Stevens & Rubin, 1970). More recent research identified a stimulus property captures the physics of lifting. A reanalysis of data from Stevens and Rubin 1970 along with a series of experiments in which object mass, size, torque, and mass distribution were manipulated, Amazeen and Turvey (1996) demonstrated that ratings of heaviness perception were a function of an object's inertia tensor.

The inertia tensor can be described as the resistance to the rotational forces of the limbs (Amazeen & Turvey, 1996; Winter, 2009, Fitzpatrick, Carello, and Turvey, 1994). To understand the inertia tensor we must revisit Newton's second law. As discussed above, this equation tells us how much force is needed to move an object (with a mass) at a given acceleration. This basic equation describes the force required to move a mass in translational movements, but it is important to note that limb movements are made about a joint (or origin, *O*), and are therefore rotational. Taking a rotational view of Newton's second law gives us the following equation:

$$\tau = I^{*}\dot{\omega} \qquad (2),$$

where τ is torque (or rotational force), $\dot{\omega}$ is rotational acceleration, and I is rotational inertia (or rotational mass). This tells us how much rotational force is needed to move an object at a given acceleration; rotational inertia is specified by a ratio of force and acceleration. Waddell et al. (2016) showed that perceived heaviness is specified by a ratio of force and acceleration, suggesting a mechanism for perceiving rotational inertia.

Research has shown that the inertia tensor is the perceptual basis for perceiving many object properties other than heaviness through haptic touch (Amazeen & Turvey, 1996). This included properties such as object length (Cabe, 2010; Pagano & Cabe, 2003; Stroop, Turvey, Fitzpatrick, & Carello, 2000), width (Turvey, Burton, Amazeen, Butwill, & Carello, 1998; Carello & Turvey, 2004), shape (Takamuku, Hosoda, & Asada, 2008), and orientation (Pagano & Turvey, 1992; Turvey, Burton, Pagaon, Solomon & Runeson, 1992). The inertial model of dynamic touch has been used to investigate tool usage in several contexts (Hartman, Kil, Pagano, & Burg, 2016; Headrick, Renshaw, Pinder, & Davids, 2012; Hove, Riley & Shockley, 2006; Kim et al., 2013), and specifically the action capabilities, or affordances (Gibson, 1979/2014) of tools (Carello, 2004; Harrison, Hajnal, Lopresti-Goodman, Isenhower & Kinsella-Shaw, 2011; Wagman & Shockley, 2011). This hypothesis has also been extended to haptic perception in the foot (Hanjal et al., 2007). Given that the inertia tensor is the perceptual basis for dynamic touch in many situations, this suggests a mechanism exists by which people can access this percept. Waddell et al., (2106) proposed such a mechanism to be ratio of muscle activity (force) to acceleration. We will further investigate this mechanism in the current study.

Context-Conditioned Variability

The relationship between an action and the states of neurons, muscles, and limbs used to perform that action varies with context (Bernstein, 1976; Linnamo, Strojnik & Komi, 2006; Doheny, Lowery & Fitzpatrick, 2008; Shapiro, Prodoehl, Corcos, & Gottlieb, 2005; Turvey, Fitch & Tuller, 1982). The same action can result from a variety of states of these variables; while different actions can also result from the same state. This context-conditioned variability results from anatomical, mechanical, and physiological sources. The current investigation will aim to show that context-conditioned variability arising from anatomical sources has similar implications for perception.

Three major sources of context-conditioned variability have been identified in the control of movement (Bernstein, 1967). Two of these sources, mechanical and anatomical, are relevant to the current discussion and investigation. To illustrate mechanically sourced context-conditioned variability, starting with the arm extended, contracting the biceps brachii at a given amount, the arm will flex at the elbow. Starting instead with the arm flexed at the elbow and then extending it, contracting the biceps brachii at the same given amount will result in a different movement. In this case, it could result in stopping, slowing, or reversing the movement of the arm. The implication here is that the relationship between a given amount of muscle contraction and a movement is not fixed (Turvey et al., 1982). Previous research in our lab has investigated this type of context-conditioned variability in heaviness perception. Participants lifted objects that varied in mass, which was in effect a manipulation of the contractile state of the biceps brachii. Results showed that perceived heaviness scaled to muscle activity and movement (Waddell et al., 2016; Waddell & Amazeen, in prep). We interpret these findings as showing that mechanically sourced context conditioned variability has similar implications for perception; the relationship between a given amount of muscle contraction and perception is not fixed.

The focus of the current set of experiments is on variability arising from anatomical factors. Consider the following arm movement examples (Turvey, et al., 1982). Starting with the arm down at the side of the body, contraction of the pectoralis major will bring the arm close to the center of the body with horizontal movement.

Starting instead with the arm held out to the side above the shoulder, contraction of the same muscle moves the arm away from the center of the body. The role of the pectoralis major in movement changes depending on the initial position of the arm about the shoulder joint in these two movements. Another example of a single arm movement illustrates anatomically sourced context-conditioned variability. The lattissimus dorsi is used to move the arm downward against a resistance. To perform the same movement but with no resistance, the lattissimus dorsi is not involved; instead the deltoid muscles control the downward movement of the arm. The same movement can be performed with different muscles.

These examples illustrate an important implication of context-conditioned variability for motor control – a given muscle does not always play the same role in movement. We are able to lift and move objects with different muscles, and the role of a muscle in movement changes. It follows that we use different muscles to perceive in the same way, and that the role of a muscle in perception can change. The goal of the current set of experiments is to show that anatomical sources of context-conditioned variability have similar implications for perception; a given muscle does not always play the same role in perception.

Current Experiments

To investigate whether muscle activity and movement in the leg combined to influence perceived heaviness in the same pattern shown in the arm by Waddell et al. (2016) participants judged the heaviness of weights with knee extension lifts in the first experiment. Leg movement and quadriceps muscle activity was recorded along with ratings of perceived heaviness. In the second experiment, the implication that the role of muscles in perception can change was investigated. Participants used three different arm lifts to judge the heaviness of objects. Arm movement and muscle activity from three arm muscles were recorded as participants performed these lifts.

In both experiments it was hypothesized that heaviness perception should be scaled to a ratio of muscle activity to movement. Specifically, regressing EMG and angular acceleration onto perceived heaviness should result in a positive exponent for EMG and a negative exponent for acceleration. The directions of these exponents should result in a psychophysical power function similar to Equation 1. It is also hypothesized that PCA analysis of the muscle activity in the second experiment should identify the changing roles of muscles across different lifts and therefore motivate a change to Equation 1. This change should suggest that study of real perception and action should include specific muscles, movements, and perception by combining them into one function.

CHAPTER 2

EXPERIMENT 1

Methods

In the first experiment, the effects of EMG and movement on perceived heaviness during knee extension lifts were investigated. The goal of this experiment was to determine whether muscle activity and movement in the leg combine to influence perceived heaviness in the same pattern shown in the arm by Waddell et al. (2016).

Participants

Eighteen undergraduate students at Arizona State University participated in exchange for credit toward an introduction to psychology course. Participants ranged in age from 18 to 22 years old. None of the participants identified any current or previous muscular or skeletal injuries to their legs, knees, hips, back, or torso that might interfere with the results.

Design

Participants lifted stimuli that varied in mass and reported their perceived heaviness compared to a standard with knee extension lifts. The stimuli varied by five levels of mass with one lift. To assess the contribution of EMG and movement in perceived heaviness during these lifts, the root mean squared value of the quadriceps muscles electromyogram (EMG) and peak angular acceleration of the leg were recorded during each lift.

Apparatus

Participants performed knee extension lifts using an Inspire Fitness M2 Multi Gym by Health In Motion, LLC (Figure 1). Participants lifted five levels of Mass (5.9

kg, 11.8 kg, 17.7 kg, 23.6 kg, and 29.5 kg). The standard had a Mass of 17.7 kg and was included in the five levels of Mass.

EMG of the muscle of interest was recorded at 1,000 Hz using a single channel, high gain amplifier (Biopac Systems, Inc.). The skin of the electrode sites was abraded with isopropyl pads before electrode placement to limit skin impedance. Disposable surface electrodes were placed on the center of the quadriceps muscles of the leg parallel to the muscle fiber. A reference electrode was placed close to the knee. Lifting kinematics were recorded using a Northern Digital Optotrak 3020 motion tracking system. This system recorded the three-dimensional positions of infared-light-emitting diodes (IREDs) at a sampling rate of 1,000Hz. Movement data were recorded from IREDs attached to the knee and roller pad while participants performed knee extension lifts.

Procedure

The standard stimulus was presented first on each trial. One of the 5 test stimuli was then presented. The standard was given an arbitrary weight of 100; participants then reported a numerical estimation of the test stimuli compared to the standard. To perform knee extension lifts participants began by sitting in the seat of the Inspire Fitness M2 Multi Gym in appropriate position so that the knees rested on the upper roller pads and feet were under the lower roller pads. Participants were instructed to raise their leg in front of them to a height at which an approximately 70-degree lift (between leg and chair leg) was achieved. Lift heights were marked with hanging targets. These targets were measured before the experiment. Participants lifted each of the five stimuli three times with the knee extension lift, resulting in a total of 15 trials. Trials were fully randomized and participants were encouraged to rest between trials to avoid fatigue. The Institutional Review Board at Arizona State University approved all procedures (see Appendix A).

Data Analysis

EMG data were filtered with a 20-500Hz Butterworth filter and then fully rectified (Criswell, 2011). The EMG (in volts) was calculated from the beginning to end of each lift. Kinematics recorded from the upper and lower leg were used to identify the beginning and end of each lift. Position data from the leg was filtered with a ten sample moving average. Angular acceleration was calculated by taking the second derivative of the angular position data using a gradient derivative method.

The root mean square (rms) EMG during the upward portion of each lift was recorded as the index of muscular effort and proxy for muscular force. Peak angular acceleration in degrees per second squared of the leg during each lift was calculated. Figures 2 and 3 show sample angular acceleration and EMG data respectively from the upward portion of knee extension lifts. This value was also obtained from the upward portion of each lift and recorded as a measure of lifting acceleration. A one-way repeated-measures Analysis of Variance (ANOVA) was conducted on perceived heaviness, EMG, and angular acceleration as functions of Mass.

To identify the underlying psychophysical power function of perceived heaviness as a function of EMG and acceleration, log values of perceived heaviness were regressed onto log values of normalized EMG and acceleration values. EMG values by were divded by participant means and then multiplied by the grand EMG mean to normalize the EMG. Normalization accounts for between subject variability that can be due to factors such as varying muscle size, skin impedance, and electrode placement (Criswell, 1998). Because we predicted that perceived heaviness should scale to the ratio of EMG to acceleration, we expected that the exponent on EMG in the power function for all experiments should be positive and the exponent on angular acceleration should be negative.

Experiment 1 Results and Discussion

Perceived Heaviness

Figure 4 shows mean perceived heaviness as a function of mass. As expected, perceived heaviness increased as mass increased. As mass increased from 5.9 kg to 29.5 kg perceived heaviness increased from 22 to 180. The main effect of mass was significant, $F(4,64) = 113.57$, $p < .05$, $\eta_p^2 = .87$. Perceived heaviness was significantly different at each level of Mass (all t's > 4.75, p's < .01).

Muscle Activity

Figure 5 shows mean rms EMG of the quadriceps muscles as a function of Mass. As Mass increased, rms EMG increased from 0.08 V to .17 V. The main effect of Mass was significant, $F(4,64) = 32.77$, $p < .05$, $\eta_p^2 = .67$. Rms EMG did not differ between 17.7 kg and 23.6 kg, $t = 1.58$, *ns*. Rms EMG differed at every other level of Mass (all t's > 3.14, p's < .05).

Acceleration

Figure 6 shows the peak angular acceleration of the leg. As Mass increased, peak angular acceleration decreased from 0.00046 deg/ms^2 to 0.00044 deg/ms^2. This main effect of Mass was significant, $F(4,64) = 2.74$, $p < .05$, $\eta_p^2 = .15$. These results replicated those found by Waddell et al. (2016). Acceleration from the 5.9 kg mass and 23.6 kg mass differed significantly, $t = 2.55$, $p < .05$. All other masses did not differ significantly (all t's < 1.93, all p's > .05).

Psychophysiological Power Function

The multiple regression using the normalized EMG and peak angular acceleration values described above was performed. The overall regression was significant, $R^2 = 0.52$, $F(2, 234) = 125.77$, $p < .05$. The regression revealed a positive exponent for EMG with a value of 2.13, $t = 15.17$, $p < .05$; and a negative exponent for Acceleration with a value of -1.69, $t = -3.20$, $p < .05$. These results are shown in Table 1. Using the resulting coefficients as exponents resulted in the following psychophysiological power function: Perceived Heaviness $= 10^{-1.88} \times \text{EMG}^{2.13} \times \text{Acceleration}^{-1.69}$. The positive exponent on rms EMG and negative exponent on Acceleration show that the data conform to the following ratio:

$$\text{Perceived Heaviness} = 10^{-1.88}\ \frac{\text{EMG}^{2.13}}{\text{Acceleration}^{1.69}}. \qquad (3)$$

Table 2 contains the resulting coefficients as exponents for each individual participant. Sixteen of the seventeen participants showed positive exponents for rms EMG, and eleven participants showed negative exponents for angular acceleration. Overall, eleven of the seventeen participants showed the pattern found by Waddell et al. (2016) of both positive rms EMG exponents and negative angular acceleration exponents. These results suggest that perceived heaviness dynamics in the leg are similar to perceived heaviness dynamics in the arm as shown by Waddell et al. (2016).

CHAPTER 3

EXPERIMENT 2

Methods

In the second experiment, the effects of EMG and movement in perceived heaviness during three arm lifts were investigated. The goal of this experiment was to determine how muscle activity and movement combined to influence perceived heaviness as muscle roles change. To do this, muscle activity was recorded from three arm muscles as participants lifted objects with three different lifts.

Participants

Seventeen undergraduate students at Arizona State University participated in exchange for credit toward an introduction to psychology course. Participants ranged in age from 18 to 21 years old. None of the participants identified any current or previous muscular or skeletal injuries to their hand, arm, neck, back, or torso that might interfere with the results.

Design

Participants lifted objects that varied in mass and report perceived heaviness compared to a standard. Participants lifted objects that varied by five levels of Mass with three lifts, resulting in a Mass (5) by Lift (3) design. The three levels of lifts included wrist flexion, elbow flexion, and forward shoulder flexion lifts. Peak arm acceleration and the root mean square of the EMG of the forearm flexors, biceps brachii, and anterior deltoid were recorded during the lifts.

Apparatus

Participants lifted a set of five stimuli plus a standard created from Polyvinyl Chloride (PVC) pipe segments filled with lead shot. Caulk and expanding foam were used to evenly distribute the lead shot throughout the cylinders and to eliminate auditory information about the contents. There were five levels of Mass (210g, 340 g, 470 g, 600 g, and 730 g). The standard had a Mass of 500 g. All stimuli had a volume of 970 cm^3. Each stimulus had a length-to-width ratio of 1.7. EMG of the muscle of interest was recorded at 1,000 Hz using a single channel, high gain amplifier (Biopac Systems, Inc.). The skin of the electrode sites was abraded with isopropyl pads before electrode placement to limit skin impedance. EMG activity of the forearm flexors, biceps brachii, and the anterior deltoid were recorded during all three lifts. We followed methods of Hagberg (1981) to record EMG from the anterior part of the deltoid muscle. Two disposable surface electrodes were placed on the center of the each muscle 2 cm apart and parallel to the muscle fiber (Criswell, 2011). A reference electrode was also placed on the wrist. Movement data were recorded from IREDs attached to the object, wrist, elbow, and shoulder while participants perform the lifts. See figure 7 for a diagram of the apparatus.

Procedure

To perform forward shoulder flexion lifts, using methods similar to those used in Hagberg (1981), participants were instructed to lift the stimuli using shoulder forward flexion to approximately 70 degrees (between the arm and the trunk). The elbow remained in a neutral position and the forearm supinated throughout the lifting procedure (Hagberg, 1981). To perform elbow flexion lifts, following the methods of Waddell et al.

(2016), participants lifted the stimuli with an elbow flexion to a height at which an approximately 70-degree lift (between table and arm) would be achieved. See figure 7 for a diagram of lifting procedures and apparatus. Lift heights were marked with hanging targets for all lifts. To perform wrist flexion lefts, participants sat at a table on which they rested their dominant arm. They were then instructed to lift the stimuli to a height at which an approximately 70-degree lift (between table and hand) would be achieved, while maintaining their forearm position on the table. These targets were measured before the experiment. In all lifts, participants reported a numerical estimation of perceived heaviness relative to a standard. Participants performed each of the three lifts with all five stimuli three times, resulting in a total of 45 trials for each participant. The Institutional Review Board at Arizona State University approved all procedures (see Appendix A).

Data Analysis

EMG values were calculated from muscle activity of the forearm flexors, biceps brachii, and anterior deltoid muscles, see figure 8 for sample data from all three muscles during the upward portion of a shoulder flexion lift, elbow flexion lift, and wrist flexion lift. Angular acceleration values were calculated from kinematic data recorded from the relative joint angles of the shoulder, elbow, and wrist. The shoulder joint angle was calculated from the position of the upper arm; the elbow joint angle was calculated from the position of the forearm and upper arm; and the wrist joint angle was calculated from the position of the hand and forearm. See figure 9 for sample angular position data from the upward portion of all three lifts. Filtering and calculation of root mean square of EMG and angular acceleration data were same as those used in the first experiment.

Principal Component Analysis

Principal Component Analysis (PCA) was used in the current experiment to determine the role of each muscle and movement during each lift. Principle components analysis is a data reduction technique that produces a set of uncorrelated composites from a large set of possibly correlated variables. This technique has been used in clinical biomechanics to reduce data to a smaller number of independent factors (Daffertshofer, Lamoth, Meijer, & Beek, 2004). PCA has been used to identify the kinematic and kinetic variables used in movements such as jumping, (Charoenpanicha, Boonsinsukhb, Sirisupc, & Saengsirisuwana, 2013; Kollias, Hatzitaki, Papaiakovou, & Giatsis, 2001), throwing (Tripp, Uhl, Mattacola, Srinivasan, & Shapiro, 2006) dance (Hollands, Wing, & Daffertshofer, 2004), and more (Boyer, Silvernail, & Hamill, 2014; Lee, Roan, Smith, 2009; Pinter, Van Swigchem, van Soest, & Rozendaal, 2008). We used PCA analysis described by Charoenpanicha et al. (2013) to identify muscle and joint movement roles across lifts. PCA was performed for each lift on EMG recorded from the three arm muscles from each participant, and on each angular acceleration measure. Muscles whose activity loaded on the first component most frequently across participants were identified as the prime mover because the first component accounts for the most variability in a data set. Likewise, joints whose angular acceleration activity loaded most frequently on the first component across participants were identified as prime contributors of acceleration to lifts.

The results from the PCA analysis motivated a change in the psychophysiological function described in Equation 1. The rms EMG of muscles and angular acceleration of joints that had important roles in each lift as revealed from the PCA analysis were worked into this new function for each lift, resulting in three functions total. To do this, just as in the first experiment, log values of perceived heaviness were regressed onto log values of normalized EMG and acceleration values. Here though, only log rms EMG values and log angular acceleration values from contributing muscles and joints were added to the equation. It was predict that perceived heaviness should scale to the ratio of EMG to acceleration, therefore it was expected that the exponents on EMG values from contributing muscles in the power functions for all lifts should be positive and the exponents on angular acceleration should be negative.

Experiment 2 Results and Discussion

Perceived Heaviness

Figure 10 shows mean perceived heaviness as a function of Mass. As expected, perceived heaviness increased as Mass increased. As Mass increased from 210g to 730g, perceived heaviness increased from 27 to 202. The main effect of Mass was significant, $F(4,72) = 119.30$, $p < .05$, $\eta_p^2 = .87$. Perceived heaviness was significantly different at each level of Mass (all, t's > 8.57; all p's < .05). There was no significant effect of Lift on perceived heaviness.

Muscle Activity

Anterior Deltoid

Figure 11 shows mean rms EMG of the anterior deltoid as a function of Mass and Lift. As Mass increased from 210g to 730g, rms EMG of the anterior deltoid increased from 0.25 V to 0.31 V. The main effect of Mass was significant, $F(4,72) = 12.48$, $p < .05$, $\eta_p^2 = .41$. The mean rms EMG of the anterior deltoid during a shoulder lift was 0.62 V, 0.18 V during an elbow lift, and 0.05 V during a wrist lift. The main effect of Lift was significant, $F(2,36) = 25.68$, $p < .05$, $\eta_p^2 = .58$. The main effects were accompanied by a significant interaction of Mass and Lift, $F(8,144) = 6.14$, $p < .05$, $\eta_p^2 = .25$. Simple effects tests revealed that as Mass increased, rms EMG of the anterior deltoid increased significantly during shoulder lifts, $F(4,72) = 11.672$, $p < .05$, $\eta_p^2 = .6$, and wrist lifts, $F(4,72) = 2.92$, $p < .05$, $\eta_p^2 = .14$, but not during elbow lifts, $F(4,72) = 1.30$, $p > .05$, $\eta_p^2 = .07$.

Biceps Brachii

Figure 12 shows mean rms EMG of the biceps brachii as a function of Mass and Lift. As Mass increased, rms EMG of the biceps brachii increased from 0.08 V to 0.12 V. The main effect of Mass was significant, $F(4,72) = 28.73$, $p < .05$, $\eta_p^2 = .61$. The mean rms EMG of the biceps brachii during a shoulder lift was 0.10 V, 0.16 V during an elbow lift, and 0.05 V during a wrist lift. The main effect of Lift was significant, $F(2,36) = 31.73$, $p < .05$, $\eta_p^2 = .64$. The main effects were accompanied by a significant interaction of mass and lift, $F(8,144) = 2.78$, $= p < .05$, $\eta_p^2 = .13$. Pairwise comparisons revealed the sources of the interaction to be significant differences between four pairs of adjacent masses (470g vs. 600g during shoulder lifts, $t(18) = 2.86$, $p < .05$; 210g vs. 340g during elbow lifts, $t(18) = 3.13$, $p < .05$; 470g vs. 600g during elbow lifts, $t(18) = 4.55$, $p < .05$; and 210g vs. 340g during wrist lifts, $t(18) = 3.12$, $p < .05$) while all other comparisons were not significant, all ts < 2.01. Though the interaction was significant, simple effects tests revealed that the main effects were present at each level of Mass and Lift (all Fs > 7.71, all ps $< .05$).

Forearm Flexors

Figure 13 shows mean rms EMG of the forearm flexors as a function of Mass and Lift. As Mass increased, rms EMG of the forearm flexors increased in from 0.21 V to 0.29 V. The main effect of Mass was significant, $F(4,72) = 19.89$, $p < .05$, $\eta_p^2 = .52$. The mean rms EMG of the forearm flexors during a shoulder lift was 0.14 V, 0.19 V during an elbow lift, and 0.41 V during a wrist lift. The main effect of Lift was significant, $F(2,36) = 55.78$, $p < .05$, $\eta_p^2 = .76$. The main effects were accompanied by a significant interaction of Mass and Lift, $F(8,144) = 2.14$, $= p < .05$, $\eta_p^2 = .11$. Pairwise comparisons revealed the sources of the interaction to be significant differences between 6 pairs of adjacent masses (470g vs. 600g during shoulder lifts, $t(18) = 2.67$, $p < .05$; 600g vs. 730g during shoulder lifts, $t(18) = 2.40$, $p < .05$; 340g vs. 470g during elbow lifts, $t(18) = 3.33$, $p < .05$; 600g vs. 730g during elbow lifts, $t(18) = 2.20$, $p < .05$; 340g vs. 470g during wrist lifts, $t(18) =2.26$, $p < .05$; 470g vs. 600g during wrist lifts, $t(18) = 2.69$, $p < .05$) while all other comparisons were not significant, all *t*s < 1.56. Though the interaction was significant, simple effects tests revealed that the main effects were present at each level of Mass and Lift (all *F*s > 8.90, all *p*s < .05).

Acceleration

Shoulder Acceleration

Figure 14 shows mean peak angular acceleration of the shoulder as a function of Mass and Lift. As Mass increased, mean peak angular acceleration of the shoulder decreased from 0.011 deg/ms^2 to 0.010 deg/ms^2. There was no effect of Mass, $F(4,72) = 1.60$, *ns*. The mean peak angular acceleration of the shoulder during a shoulder lift was 0.024 deg/ms^2, 0.0057 deg/ms^2 during an elbow lift, and 0.0033 deg/ms^2 during a wrist lift. The main effect of Lift was significant, $F(2,36) = 221.73$, $p < .05$, $\eta_p^2 = .92$. Simple effects tests revealed the main effect of Lift was significant at all three levels of lifts (all *F*s > 41.84, all *p*s < .05). There was no significant interaction of Mass and Lift, $F(8,144) = .528$, *ns*.

Elbow Acceleration

Figure 15 shows mean peak angular acceleration of the elbow as a function of Mass and Lift. As Mass increased, mean peak angular acceleration of the elbow decreased from 0.024 deg/ms^2 to 0.021. The main effect of Mass was significant, $F(4,72) = 3.83$, $p < .05$, $\eta_p^2 = .16$. The mean peak angular acceleration of the elbow during a shoulder lift was 0.018 deg/ms^2, 0.034 deg/ms^2 during an elbow lift, and 0.013 deg/ms^2 during a wrist lift. The main effect of Lift was significant, $F(2,36) = 28.89$, $p < .05$, $\eta_p^2 = .62$. Simple effects tests revealed the main effect of Lift was significant at all three levels of lifts (all *F*s > 41.95, all *p*s < .05). There was no significant interaction of Mass and Lift, $F(8,144) = 1.64$, *ns*.

Wrist Acceleration

Figure 16 shows mean peak angular acceleration of the wrist as a function of Mass and Lift. As Mass increased, mean peak angular acceleration of the elbow decreased from 0.042 deg/ms^2 to 0.036. The main effect of Mass was not significant, $F(4,72) = 1.78$, *ns*. The mean peak angular acceleration of the elbow during a shoulder lift was 0.023 deg/ms^2, 0.026 deg/ms^2 during an elbow lift, and 0.067 deg/ms^2 during a wrist lift. The main effect of Lift was significant, $F(2,36) = 48.37$, $p < .05$, $\eta_p^2 = .73$. Simple effects tests revealed that acceleration during a wrist lift differed significantly from elbow lifts, $F(1,18) = 101.31$, $p < .05$, $\eta_p^2 = .85$, and shoulder lifts, $F(1,18) = 56.48$,

$p < .05$, $\eta_p^2 = .76$. However, writ acceleration did not differ between elbow and shoulder lifts, $F(1,18) = 0.26$, *ns*. There was a significant interaction of Mass and Lift, $F(8,144) = 2.88$, $p < .05$, $\eta_p^2 = .14$. Simple effects tests revealed that as Mass increased, mean peak angular acceleration of the wrist decreased significantly during wrist lifts, $F(4,72) = 5.46$, $p < .05$, but not during elbow lifts, $F(4,72) = 1.45$, *ns,* or shoulder lifts, $F(4,72) = .30$, *ns*.

Principal Component Analysis

Results of the PCA on muscle activity from the anterior deltoid, biceps brachii, and forearm flexors are shown in figure 17. The muscle whose activity loaded most frequently on the first component during shoulder, elbow, and wrist lifts was the forearm flexors. Results of the PCA on angular acceleration from the shoulder, elbow, and wrist are shown in figure 18. The joint whose angular acceleration loaded most frequently on the first component during shoulder lifts was the shoulder, the elbow during elbow lifts, and the wrist during wrist lifts.

Principal Component Regression

The previous PCA analysis revealed that forearm flexor muscle activity loaded on the first component most frequently across participants in all three lifts, and the angular acceleration from each lift's corresponding joint loaded most frequently on the first component across participants. The same regression procedure from experiment 1 was performed for each lift. The results of the PCA determined which rms EMG and angular acceleration values were used in each regression. In the first regression, perceived heaviness was regressed onto rms EMG of the forearm flexors and angular acceleration of the shoulder during shoulder lifts. The overall regression was significant, $R^2 = 0.16$, $F(2, 272) = 20.57$ $p < .05$. The regression revealed a positive exponent for EMG with a value of 1.70, $t = 7.13$, $p < .05$; and a negative exponent for Acceleration with a value of -0.19, $t = -1.70$, $p < .05$. Using the resulting coefficients as exponents resulted in the following psychophysiological power function for shoulder lifts: Perceived Heaviness = $10^{5.01}$ × Forearm Flexors rms $EMG^{1.70}$ × Shoulder $Acceleration^{-0.19}$.

In the second regression, perceived heaviness was regressed onto rms EMG of the forearm flexors and angular acceleration of the elbow during elbow lifts. The overall regression was significant, $R^2 = 0.17$, $F(2, 272) = 28.63$ $p < .05$. The regression revealed a positive exponent for EMG with a value of 1.44, $t = 7.20$, $p < .05$; and a negative exponent for Acceleration with a value of -0.10, $t = -1.03$, $p < .05$. Using the resulting coefficients as exponents resulted in the following psychophysiological power function for shoulder lifts: Perceived Heaviness = $10^{4.05}$ × Forearm Flexors rms $EMG^{1.44}$ × Elbow $Acceleration^{-0.10}$.

In the third regression, perceived heaviness was regressed onto rms EMG of the forearm flexors and angular acceleration of the wrist during wrist lifts. The overall regression was significant, $R^2 = 0.13$, $F(2, 272) = 20.55$ $p < .05$. The regression revealed a positive exponent for EMG with a value of 1.31, $t = 5.85$, $p < .05$; and a negative exponent for Acceleration with a value of -0.65, $t = -5.20$, $p < .05$. Using the resulting coefficients as exponents resulted in the following psychophysiological power function for shoulder lifts: Perceived Heaviness = $10^{3.06}$ × Forearm Flexors rms $EMG^{1.44}$ × Wrist $Acceleration^{-0.65}$. These results suggest that perceived heaviness dynamics in the arm is similar across lifts, and that the forearm flexors are the most relevant muscle for perceived heaviness in the arm.

CHAPTER 4

GENERAL DISCUSSION

Two implications for perception from anatomically sourced context-conditioned variability - inspired by those from motor control - refer to the changing roles of muscles in perception. The first was that different muscles can be used to make the same perception. To test this, participants lifted objects with their legs and reported perceived heaviness. The second implication for perception was that a muscle's role in perception can change. This was tested in the second experiment in which objects were lifted with different arm lifts.

Different Muscles, Same Perception

Laboratory experiments often isolate the muscles used to lift (e.g., De Moree, 2014; Waddell et al., 2016). However, perceivers in the real world regularly use different muscles to obtain the same perception. For example, I may use the muscles in my arms, my back, my chest, or my legs to lift a box and perceive its heaviness. Two experiments asked whether the process for perceiving heaviness is the same across such scenarios. In the first experiment, we compared perceived heaviness during leg extensions to perceived heaviness during elbow lifts. In the second experiment, we compared perceived heaviness across three arm lifts (using the shoulder, the elbow, or the wrist). The goal was to determine whether the psychophysiological power function describing perceived heaviness as a function of a ratio of muscle activity to acceleration would be consistent across different muscles.

Regressing perceived heaviness onto EMG from the quadriceps femoris and angular acceleration of the leg in Experiment 1 resulted in the following similar psychophysiological power function: Perceived Heaviness $= 10^{-1.88} \times \text{EMG}^{2.13} \times \text{Acceleration}^{-1.69}$. The positive EMG rms exponent and negative Acceleration exponent showed that as expected, the data conformed to a ratio inspired by Newton's Second law and proposed by Waddell et al. (2016). The principal component regressions in experiment 2 also yielded psychophysiological functions with the same form as that found in Waddell et al. (2016). The EMG exponents of these functions were positive and acceleration exponents were negative. This is evidence that forearm flexors EMG and lift-corresponding angular accelerations combined in psychophysiological power functions for perceived heaviness that are similar to the function describing the same perception during a leg lift. This suggests that the dynamics of heaviness perception are similar across different lifts.

The exponent magnitudes on the resulting psychophysiological function from experiment 1 also supported findings from Waddell et al. (2016). Results from both Waddell et al. (2016) and experiment 1 in the current investigation revealed EMG exponents larger in magnitude than the angular acceleration exponents (see equations 1 and 3). Furthermore, similar to results found by Waddell et al. (2016), the majority of individual participant functions in experiment 1 showed the proposed pattern of positive exponents for EMG and negative exponents for angular acceleration (see table 2). In psychophysical power law relationships, the magnitudes of exponents represent the saliency of properties for perception (Stevens, 1957; Stevens, 1960). The magnitude differences of the exponents from both studies suggested that while both muscle activity and movement combined for heaviness perception, muscle activity was more salient for this perception. In addition eleven out of seventeen participants showed this pattern.

Overall, the results suggest that the dynamics of heaviness perception in the arm during an elbow flexion lift (Waddell et. al, 2016), multiple arm lifts (experiment 2) and the leg (experiment 1) are similar. We use different muscles to make the same perception.

Roles of Muscles in Heaviness Perception

We perform countless lifts everyday to perceive heaviness. I might use an elbow flexion to lift a bag, or a forearm flexion to lift my pencil. In each lift the prime mover changes – it is the bicep when I lift my bag, and the forearm flexors when I lift my pencil. The second experiment asked whether the muscle most relevant for heaviness perception changes in a similar way. To do this, the dynamics of perceived heaviness were explored across three different arm lifts. Principal component analysis was performed on the muscle activity and movement from the muscles and joints of interest during three arm lifts. It was hypothesized that this analysis should reveal that the role of each muscle and movement changed across each lift. For example, it was expected that the during an elbow flexion lift, muscle activity from the biceps brachii and elbow angular acceleration loaded most frequently on the first components and the same pattern would be seen for the anterior deltoid and shoulder angular acceleration during a forward shoulder flexion lift. Muscles and movements that loaded most frequently on the first component would then be interpreted as being most relevant or salient to participants when making judgments of perceived heaviness.

The Principal component analysis in Experiment 2 revealed that during forward shoulder flexion lifts, muscle activity from the forearm flexors loaded most frequently on the first component, and angular acceleration from the shoulder loaded most frequently on the first component. During elbow flexion lifts, muscle activity from the forearm flexors loaded most frequently on the first component, and angular acceleration from the elbow loaded most frequently on the first component. Finally, during wrist flexion lifts, muscle activity from the forearm flexors loaded most frequently on the first component, and angular acceleration of the wrist loaded most frequently on the first component. The overall pattern from this analysis showed that across all three lifts, forearm flexors muscle activity loaded on the first component most frequently, and the angular acceleration from each lift's corresponding joint loaded most frequently on the first component across participants (see figures 17 and 18). These results suggest the forearm flexor and angular acceleration of the corresponding joint were the most relevant for heaviness perception.

While these findings do not support the hypothesis that the role of a particular muscle in heaviness perception changes across lifts as expected, it is clear that the roles of movements across lifts changed. Principal components analysis revealed that as lifts changed, the acceleration source relevant to the perceiver changed accordingly. This is consistent with research that has shown how movements generate the information used to perceive heaviness (Amazeen, 2014; Greer, 1989; Streit, Shockley, Morris, & Riley, 2007; Streit, Shockley, & Riley, 2007). In an investigation of the size weight illusion, participants lifted stimuli in one of two ways, by either lifting objects and setting them onto either a table or small pedestal before reporting perceived heaviness (Amazeen, 2014). Participants who performed the task in which width was more relevant (placing the object onto the pedestal) experience a stronger size-weight illusion associated with the width of the stimuli. The information used to perceive heaviness was influenced by the action. The current results similarly suggest that the movement used to perceive heaviness is influenced by the specific lift used.

Implications for the Inertia Tensor

Forearm flexor muscle activity was the most relevant muscle for perceiving heaviness across all three arm lifts. This finding was surprising given that the forearm flexor was not the prime mover across all lifts. The anterior deltoid acted directly to produce the shoulder lift, the biceps brachii to produce the elbow lift, and forearm flexors to produce the wrist lift. We expected to see a similar pattern when considering perceived heaviness, but instead found that the forearm flexors loaded most frequently on the first component across all lifts – it was the most important muscle for heaviness perception. Though this finding was unexpected, it is important in the context of the previous inertia tensor discussion. It supports using the wrist as the origin of I_{xyz} because the forearm flexors act on the wrist. The psychophysiological function suggests that forearm flexors are involved in perception because that is the muscle tied to the invariant properties of the object.

There is evidence to show that haptic perception is tied to the I_{xyz} about the wrist (Pagano, et al., 1993). As previously discussed, limb movements are rotational about a joint (or origin, O). Any change in the O about which I_{xyz} is calculated will change components of I_{xyz}. Therefore, to calculate I_{xyz} that scales appropriately with an object property perceived by haptic touch, the relevant O must be determined for these types of experiments. To do this, participants wielded rods about different points of rotation (joints) and reported their weights and perceived reachable distance. Perceived reachable distance remained invariant across the shoulder, elbow, and wrist. When allowed to wield objects both freely and restricted, participants reported perceive reachable distances that scaled to I_{xyz} computed about the wrist. I_{xyz} about the wrist was invariant across movements. Several studies have since calculated I_{xyz} about the wrist in haptic perception experiments (e.g. Amazeen et al., 1996; Kingma et al., 2004; Streit et al., 2007). In light of this, it is not surprising to find heaviness perception relies mainly on muscle activity from the forearm flexor.

Toward a Complete Account of Heaviness Perception

The psychophysiological functions from the current experiments showed that perceived heaviness dynamics were similar across limbs and lifts. However, the fact that these functions did not explain a large portion of variance in perceived heaviness suggests that more research is needed to identify the appropriate properties contributing to this perception. This low model prediction may be a result of measure selection. Participants in this study experienced an entire perception action event involving lifting a stimulus and reporting its heaviness. Our goal was to select the EMG and acceleration measures that best captured this perception action event. We selected peak angular acceleration and rmsEMG. This is in line with previous research on muscle activity (De Morree, et al., 2014; Waddell et al., 2016) in perceived heaviness. But it is important to realize that there are several other parts of this event that participants may have been using for perception. Perhaps participants were paying more attention to the peak EMG, or an average acceleration, or some other part of the event that may be better measured in another way. Future studies will explore these measures in an attempt to best capture the perception action event.

The rms EMG was used as the proxy for force in the current experiments. It is important to note that this may not be the most accurate measure of the sensation of force, which may have resulted in the low model prediction. When a muscle contracts, neural impulses originate in the primary motor cortex and travel down the corticospinal tract to motor neurons. Action potentials from motor neurons travel to the muscle fiber, stimulating it to contract. Electromyography detects the summed electrical activity generated by these action potentials in the muscle fiber. However, research has suggested that the perception of effort or heaviness is not the awareness of peripheral signals, like those in the muscle, but the central motor command originating in the motor cortex sent to the muscle. When participants lifted objects with fatigued and non fatigued arms, movement related cortical potential varied with perception of effort (DeMorree et al., 2012). This line of research suggests that using rms EMG to capture the sensation of muscular force may not appropriately capture participants' sensation of force, and that the use of this measure in the current experiments may explain the lack of model fit.

The muscles measured from in this study may also have contributed to this low model prediction. We measured from just three muscles in the second experiment in this study - the forearm flexors, biceps brachii, and anterior deltoid. These muscles are the prime movers in their corresponding lifts (Criswell, 2011). Prime movers are however not the only muscles involved in a movement (Siegelbaum & Hudspeth, 2000). An elbow lift, for example involves an antagonist pair of muscles, the biceps brachii and triceps brachii. The biceps brachii contract to flex at the elbow, and the triceps brachii flex to slow and reverse the arm's movement. People use both muscles to lift. People may also be using both muscles to perceive heaviness. By not measuring all of the muscles involved in a lift we may not have captured what people are attending to in this perception action event. Future research will need to measures from any and all muscles involved in a lift. The current study suggests that a more complete account of heaviness perception will be a result of considering the many muscles and EMG measures involved in perceived heaviness.

Conclusions

Context conditioned variability has implications for motor control. One is that the relationship between a given amount of muscle activity and movement is not fixed. The same has been found for perception in studies that measure perceived heaviness of changing masses; the relationship between a given amount of muscle activity and perception is not fixed (Waddell et al., 2016, Waddell & Amazeen, in prep). Another implication for motor control is that different muscles can perform the same movement. This study showed that this implication from context conditioned variability also holds for perception. Regardless of limb or lift, participants in this study scaled their perceptions of heaviness to this combination of muscle activity and movement. Different muscles contribute to the same heaviness perception.

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APPENDIX A

TABLES AND FIGURES

Table. 1

Results of Multiple Regression with Normalized EMG and Acceleration Values

Variable	B	SE(*b*)	β	*t*	Sig. (*p*)
(Constant)	-1.88	1.79		-1.05	0.294
rms EMG	2.13	0.14	0.69	15.17	0.000
Acceleration	-1.69	0.53	-0.15	-3.20	0.002

Note. $R^2 = 0.52$

Table. 2

Estimated Exponents from Individual Participant Multiple Regressions

Participant	rms EMG	Angular Acceleration	R^2	Sig. (p)
1	0.95	-1.36	0.11	0.75
2	1.83	-3.33	0.68	0.15
3	2.64	-0.80	0.86	0.23
4	2.34	1.42	0.53	0.80
5	2.97	-3.93	0.90	0.01
6	1.70	-0.51	0.63	0.70
7	1.19	3.94	0.75	0.15
8	1.77	2.27	0.79	0.13
9	4.17	-4.39	0.92	0.03
10	3.30	1.79	0.66	0.78
11	1.07	-1.07	0.75	0.50
12	2.61	-1.44	0.86	0.48
13	4.14	1.23	0.87	0.49
14	2.70	-4.68	0.74	0.19
15	4.60	-1.28	0.88	0.74
16	-0.47	1.22	0.02	0.78
17	1.93	-0.67	0.74	0.47

Figure. 1

Figure 1. Experiment 1 lifting apparatus. Participants used the Inspire Fitness M2 Multi Gym to lift 5 levels of Mass. Participants performed knee extension lifts to approximately 70 degrees (see right panel).

Figure. 2

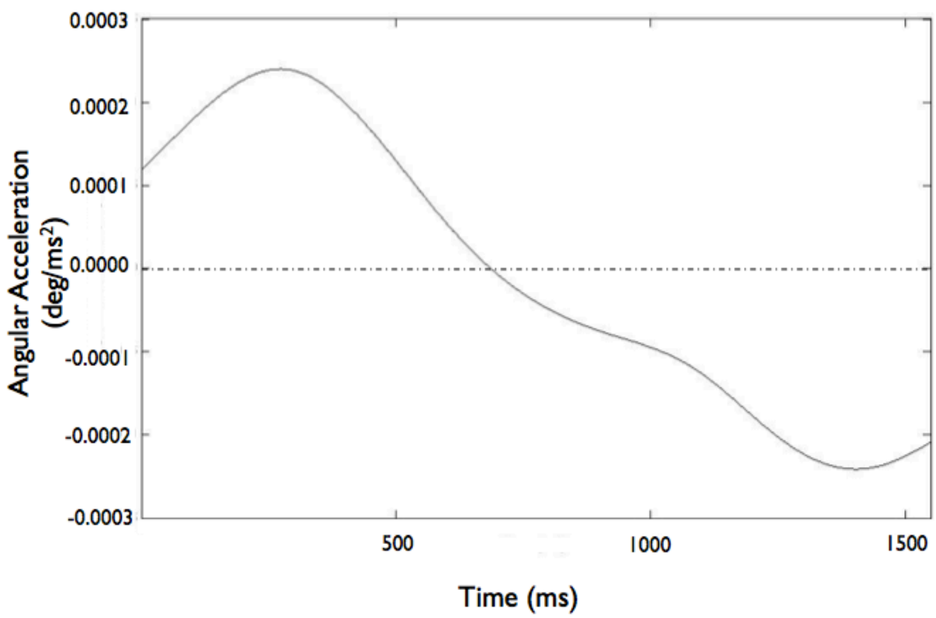

Figure 2. Sample angular acceleration (deg/ms^2)recorded from the roller pad during upward portion of knee flexion lift. Peak acceleration values were used as the measure of angular acceleration.

Figure. 3

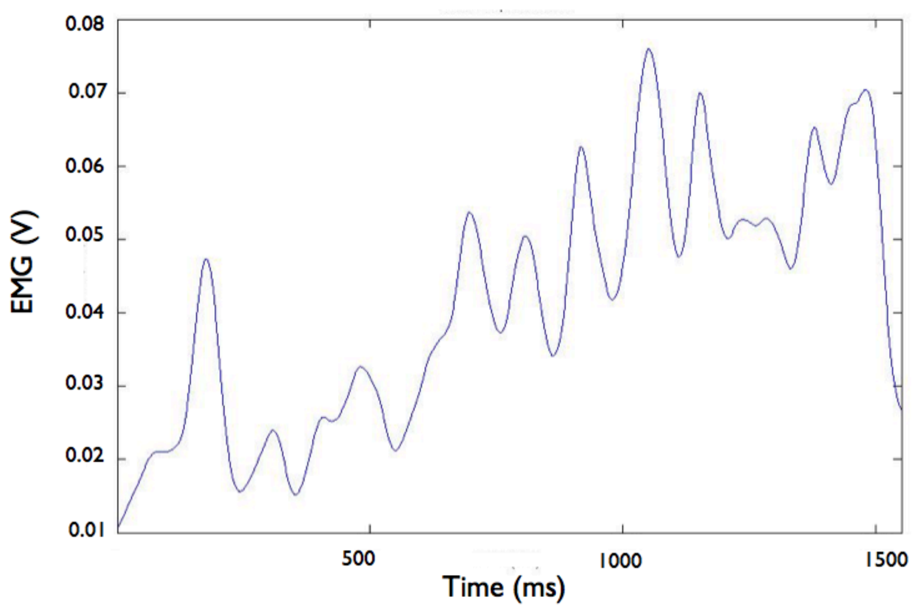

Figure 3. Sample EMG (V) from the quadriceps muscles during upward portion of a knee flexion lift. Rms EMG was used as the measure of muscle activity.

Figure. 4

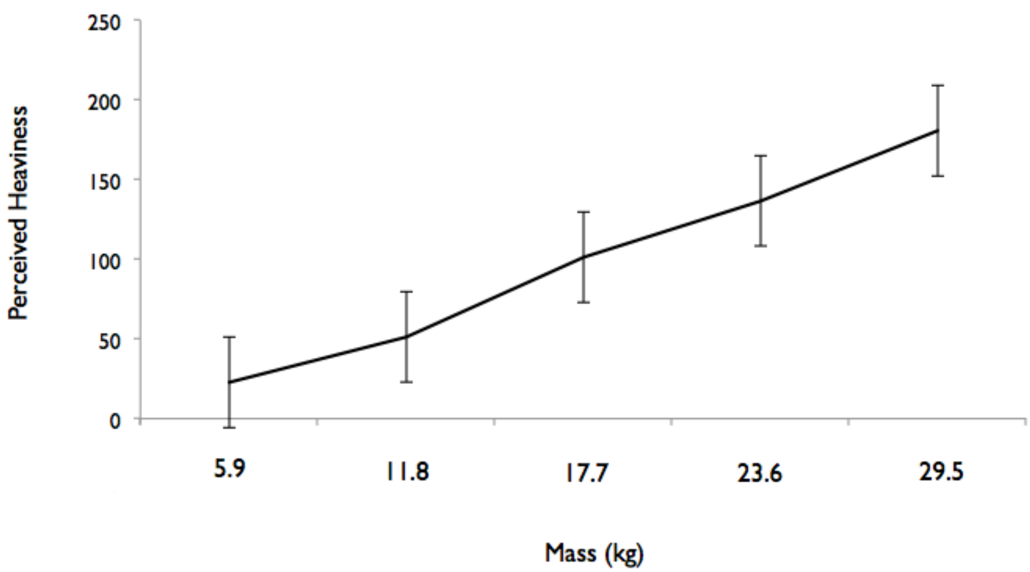

Figure 4. Mean perceived heaviness ratings of all stimuli relative to a standard of 100.

Figure. 5

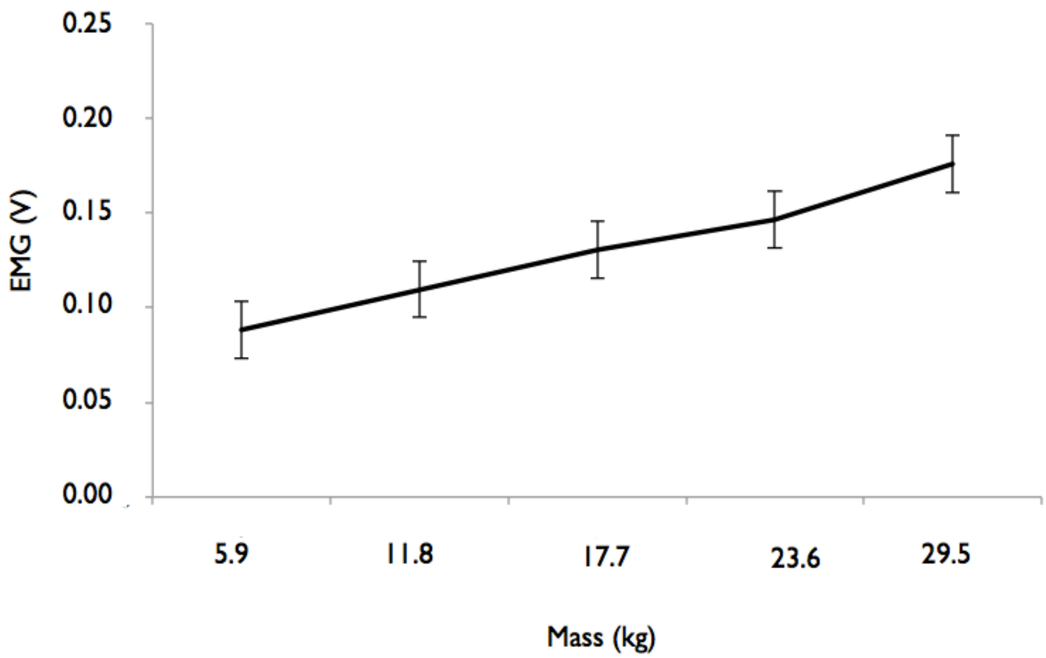

Figure 5. Mean rms EMG (V) from the quadriceps muscles as a function of Mass.

Figure. 6

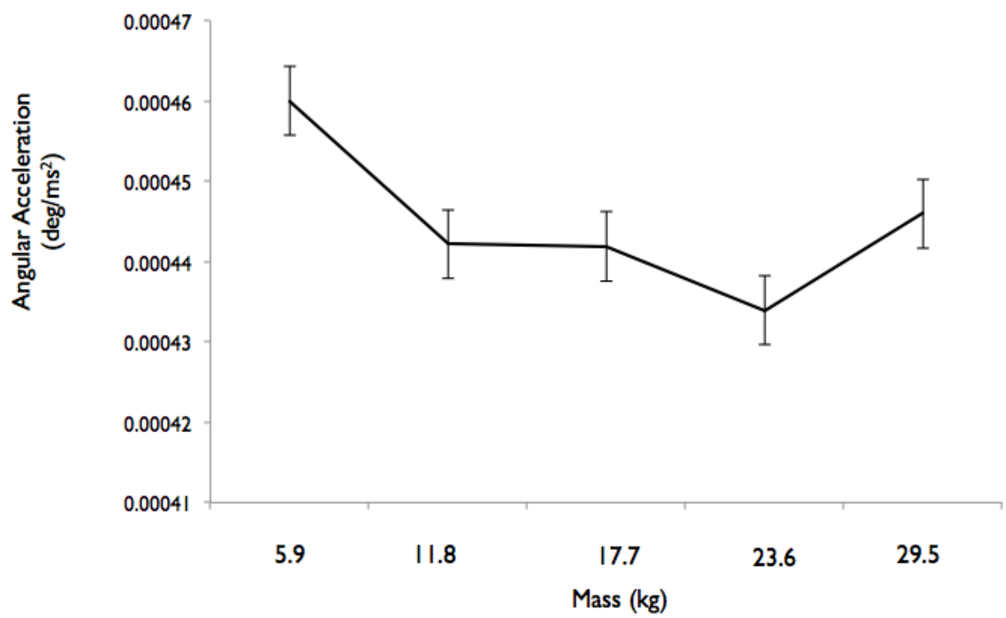

Figure 6. Mean peak angular acceleration (deg/ms^2) of all stimuli as a function of Mass.

Figure. 7

Figure 7. Lifting procedure for Experiment 2. Participants will lift stimuli with three lifts: wrist flexion (top panels), elbow flexion (middle panels), and forward shoulder flexion (lower panels), all to approximately 70 degrees.

Figure. 8

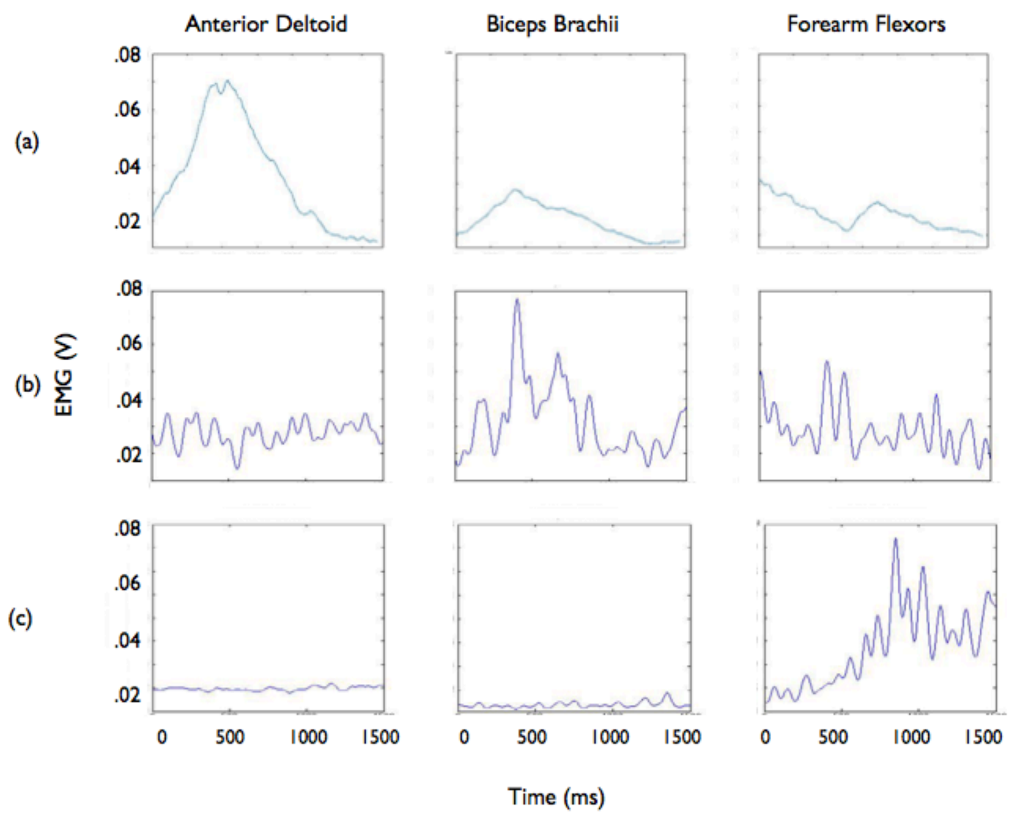

Figure 8. Sample EMG from Anterior Deltoid, Biceps Bracii, and Forearm Flexors during upward portion of an (a) shoulder lift, (b) elbow lift, and (c) wrist lift. Rms EMG was used as the measure of muscle activity.

Figure. 9

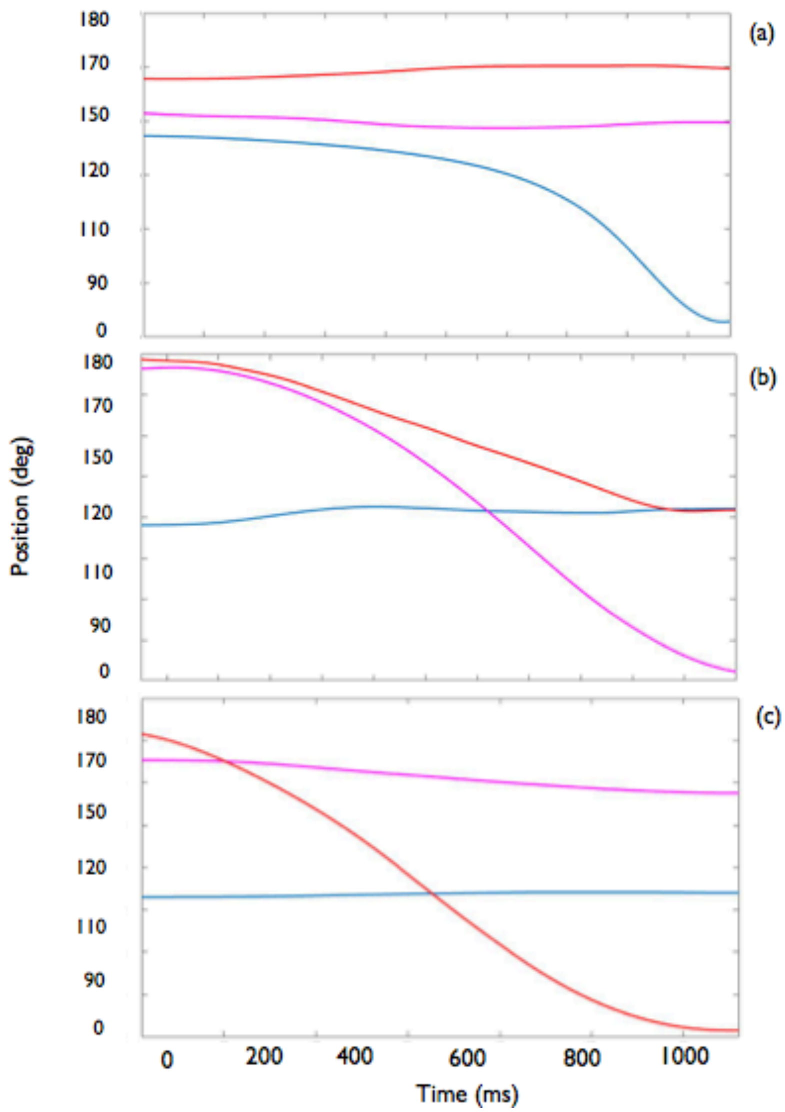

Figure 9. Sample Sample angular position data from the Shoulder, Elbow, and wrist during upward portion of an (a) shoulder lift, (b) elbow lift, and (c) wrist lift. Angular acceleration was calculated from the position data. Peak angular acceleration was used as the measure of acceleration.

Figure. 10

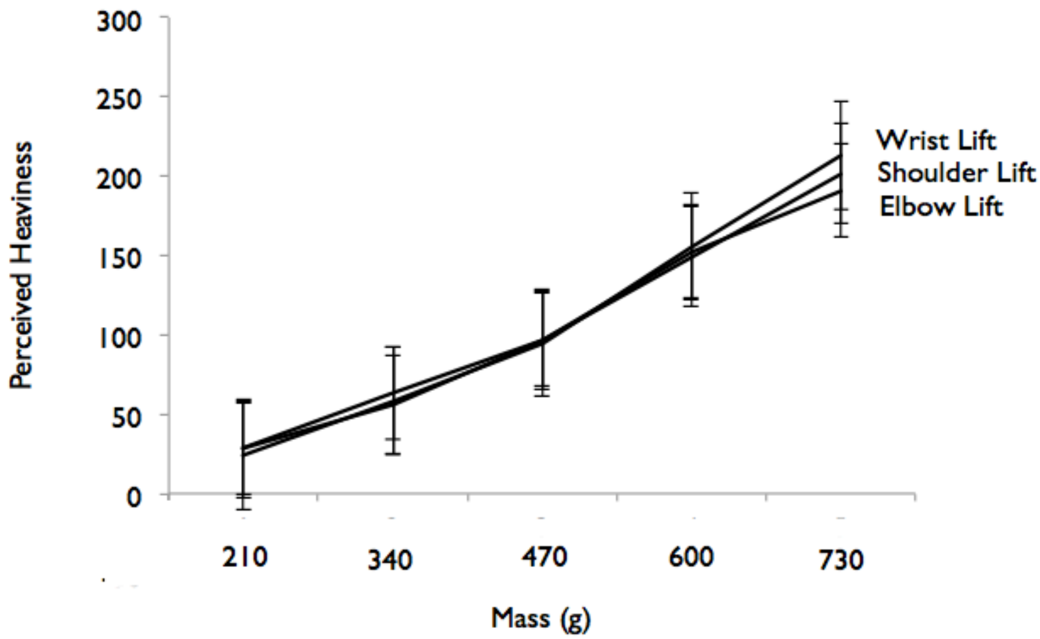

Figure 10. Mean perceived heaviness ratings of all stimuli for all lifts relative to a standard of 100.

Figure. 11

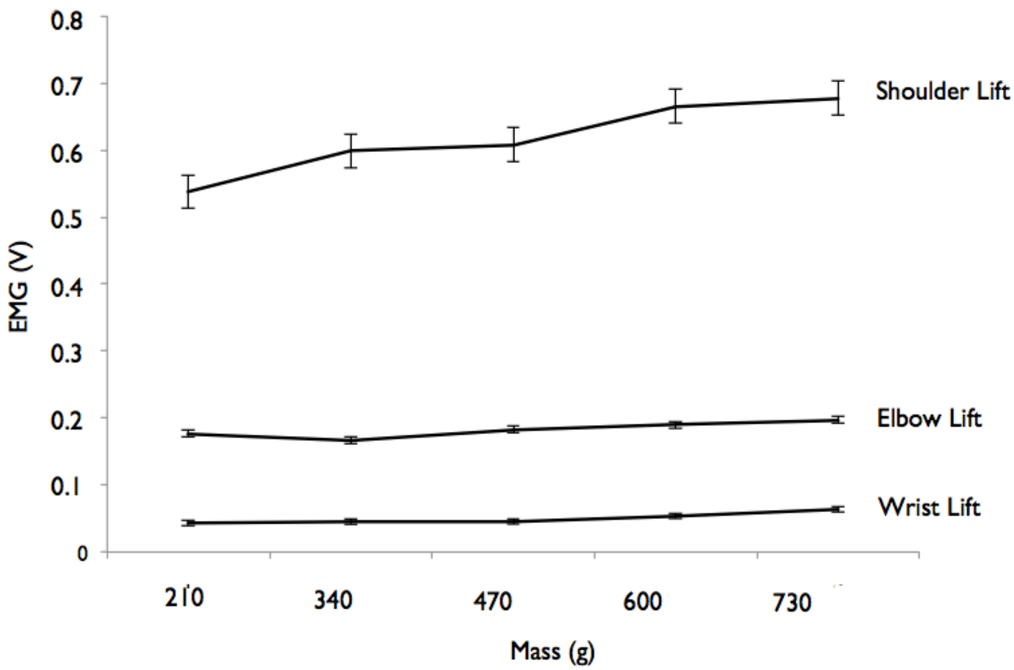

Figure 11. Mean rms EMG in volts (V) recorded from the anterior deltoid during shoulder, elbow, and wrist lifts.

Figure. 12

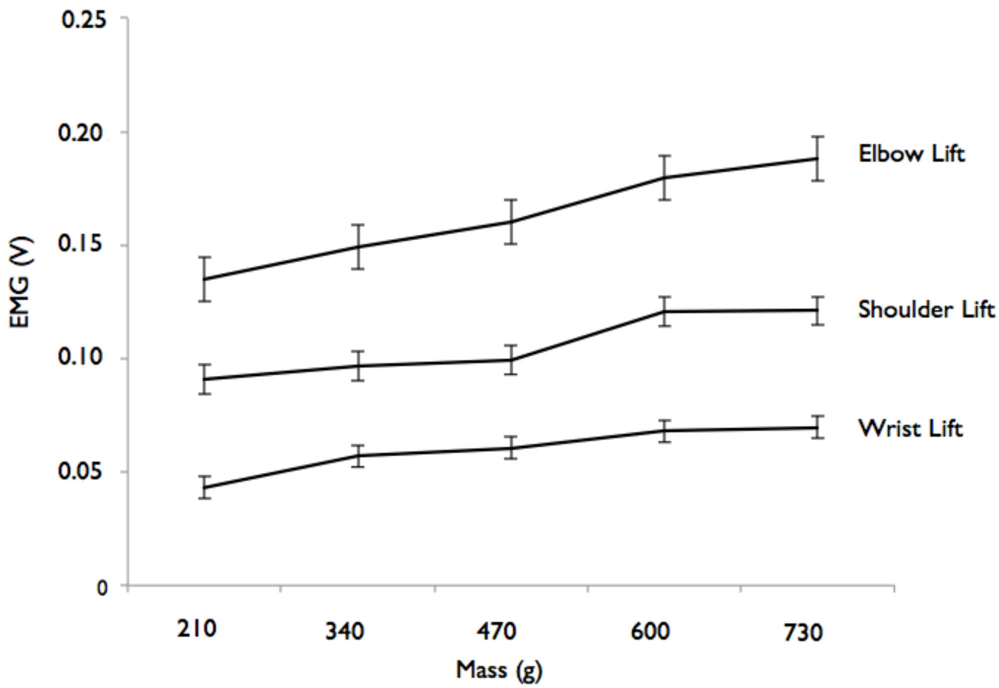

Figure 12. Mean rms EMG in volts (V) recorded from biceps brachii during shoulder, elbow, and wrist lifts.

Figure. 13

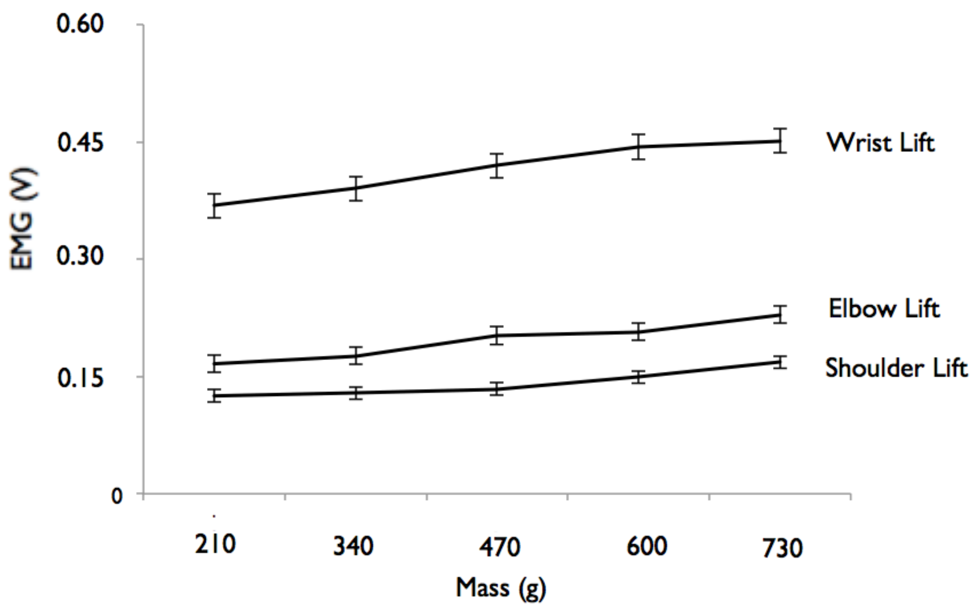

Figure 13. Mean rms EMG in volts (V) recorded from forearm flexors during shoulder, elbow, and wrist lifts.

Figure. 14

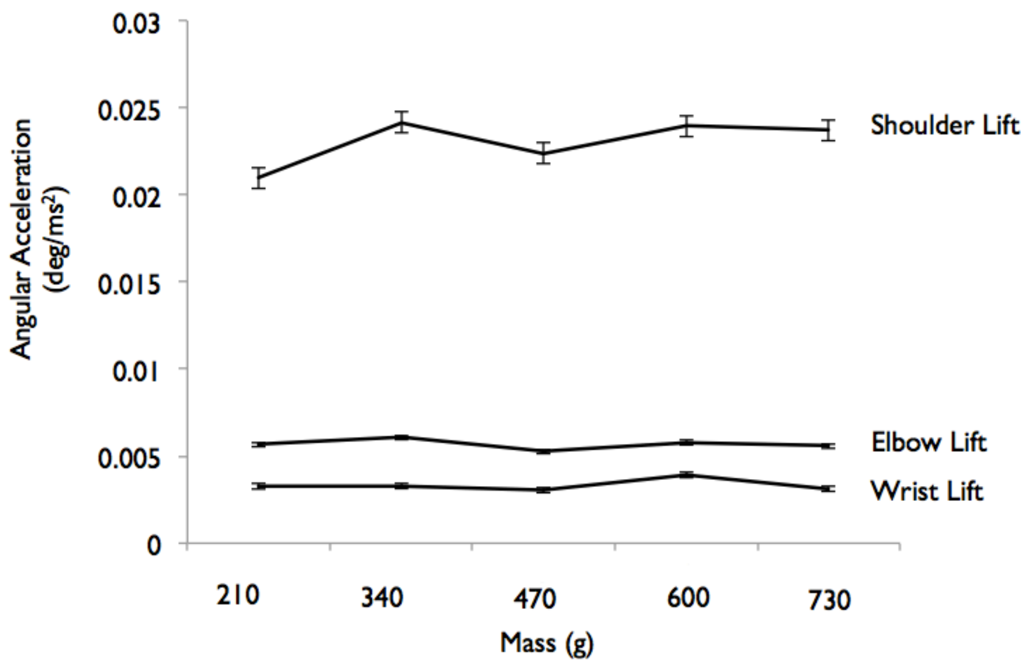

Figure 14. Mean peak angular acceleration (deg/ms^2) recorded from the shoulder during shoulder, elbow, and wrist lifts.

Figure. 15

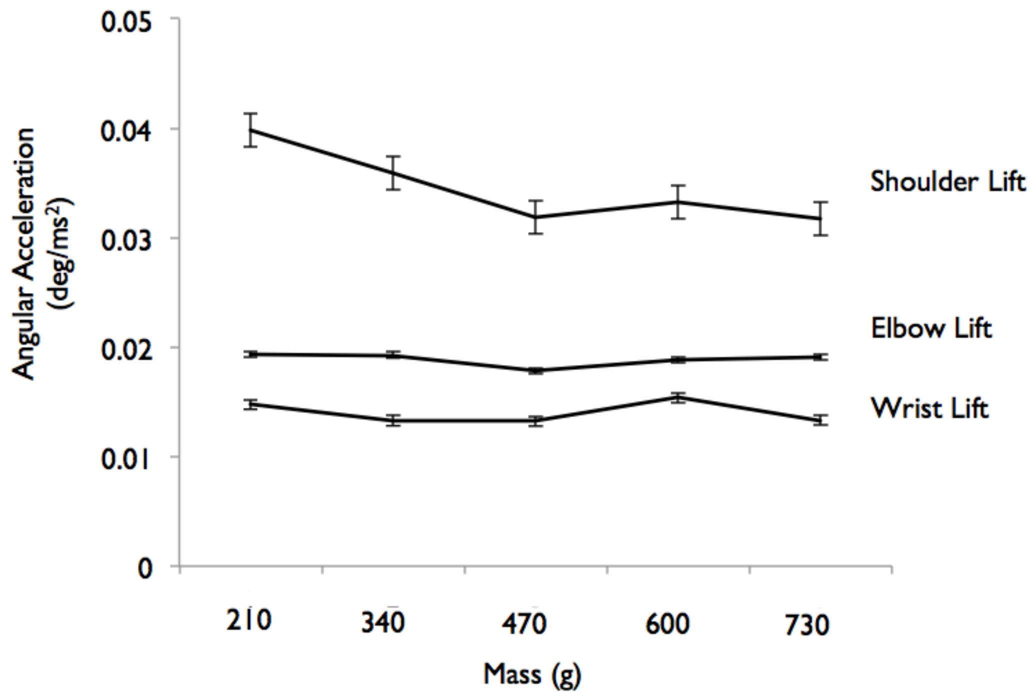

Figure 15. Mean peak angular acceleration (deg/ms^2) recorded from the elbow during shoulder, elbow, and wrist lifts

Figure. 16

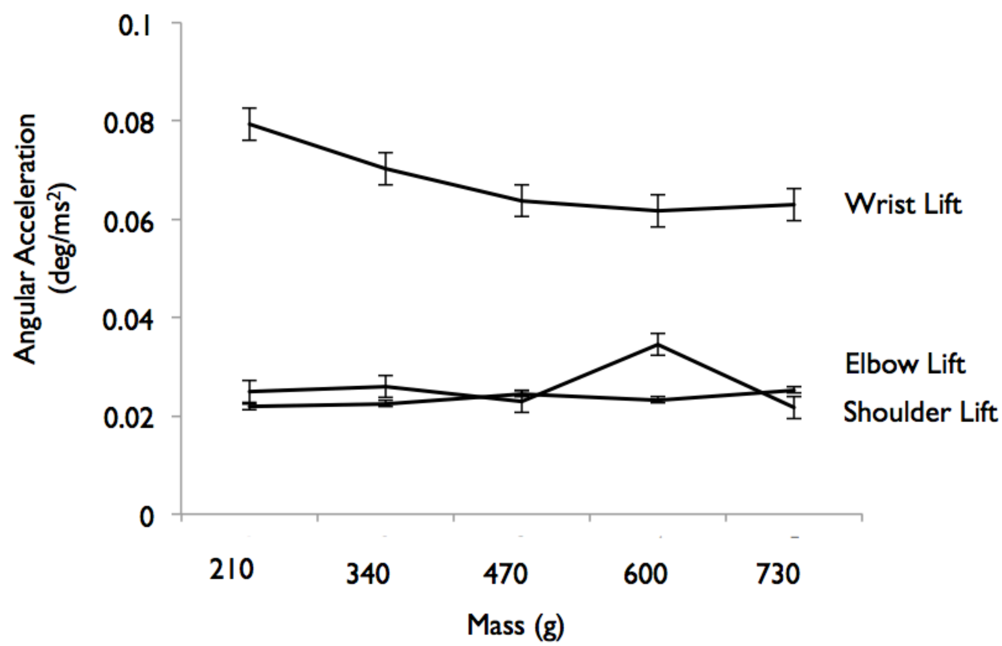

Figure 16. Mean peak angular acceleration (deg/ms^2) recorded from the wrist during shoulder, elbow, and wrist lifts.

Figure. 17

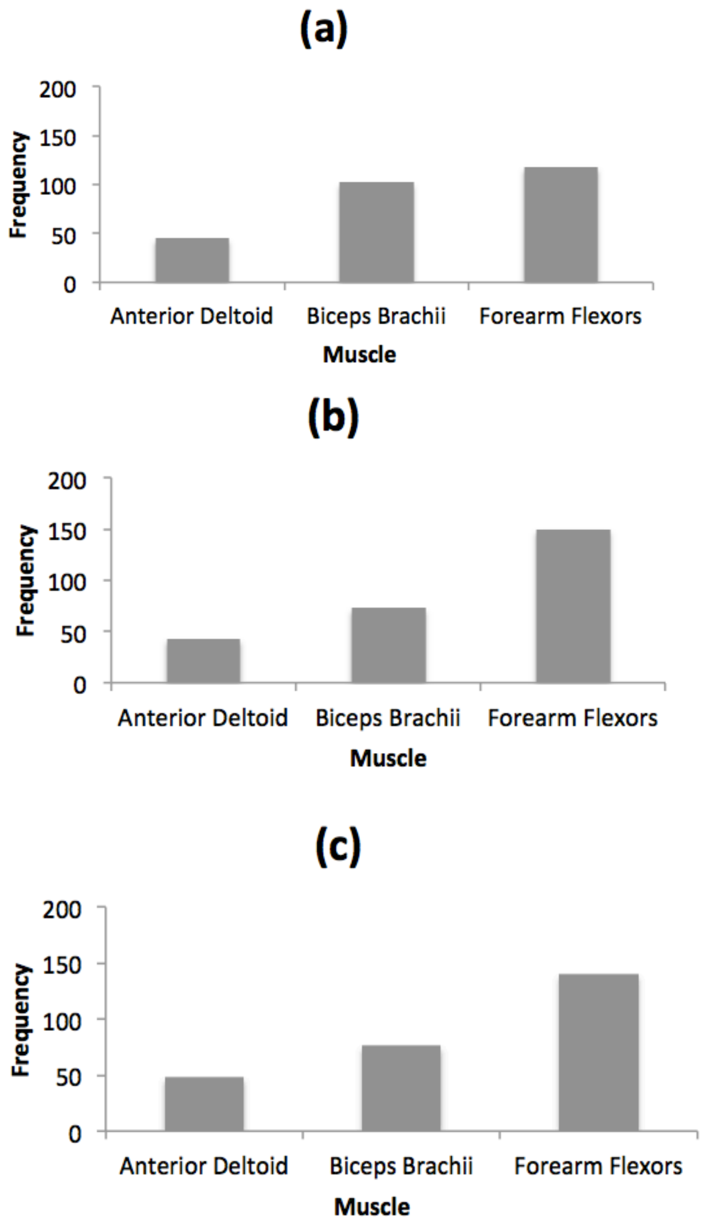

Figure 17. The principal muscle sources revealed by the PCA analysis during (a) shoulder lifts, (b) elbow lifts, and (c) wrist lifts. The y-axis represents the frequency of loading on the first component.

Figure. 18

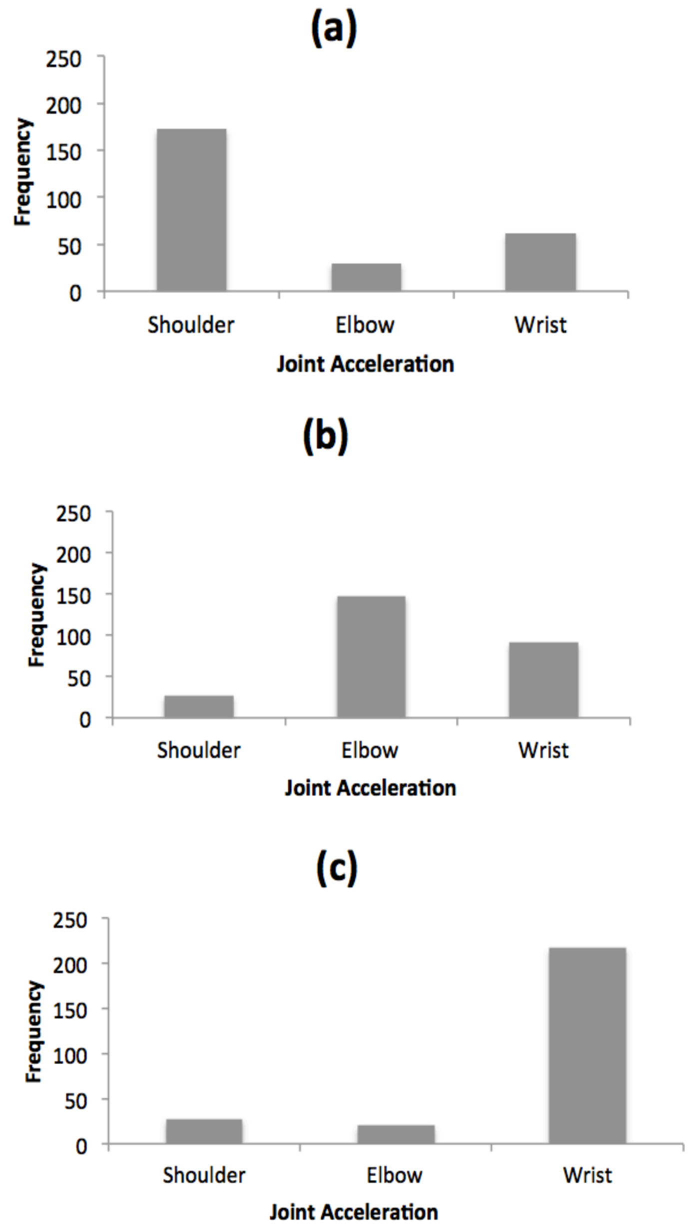

Figure 18. The principal acceleration sources revealed by the PCA analysis during (a) shoulder lifts, (b) elbow lifts, and (c) wrist lifts. The y-axis represents the frequency of loading on the first component.

APPENDIX B

IRB APPROVAL LETTER

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APPROVAL: MODIFICATION

Eric Amazeen
Psychology
480/727-7079
Eric.Amazeen@asu.edu

Dear Eric Amazeen:

On 9/9/2015 the ASU IRB reviewed the following protocol:

Type of Review:	Modification
Title:	Weight Perception
Investigator:	Eric Amazeen
IRB ID:	1301008720
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• Weight%20Perception%20Informed%20Consent-3.pdf, Category: Consent Form; • Weight%20Perception%20IRB%20application%20Protocol.docx, Category: IRB Protocol;

The IRB approved the modification.

When consent is appropriate, you must use final, watermarked versions available under the "Documents" tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc: Morgan Waddell
Lana Rogoff