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RESEARCH ARTICLE

# Evaluating the contributions of muscle activity and joint kinematics to weight perception across multiple joints

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**Abstract** Perceived heaviness is clearly a function of muscle activity: objects feel heavy, in part because they are lifted with more force than lighter feeling objects. Recent research showed that participants scale their perceptions to the ratio of muscle activity to lift acceleration during elbow lifts (Waddell et al. J Exp Psychol Hum Percept Perform 42:363–374, 2016). The current study sought psychophysiological functions relating perceived heaviness to EMG and peak lift acceleration across multiple lifts employing different muscles as prime movers. Participants lifted objects with three arm lifts—shoulder, elbow, and wrist—and reported perceived heaviness. In each lift, EMG was recorded from the anterior deltoid, biceps brachii, and forearm flexors, and peak angular acceleration was recorded about each joint. The resulting psychophysiological functions revealed the hypothesized ratio of muscle activity to peak lift acceleration in all lifts. Principal component regressions showed that the EMG of the forearm flexors and peak acceleration of the lifting joint were most relevant for perceived heaviness. The special role of forearm flexors in perceiving heaviness across different lifts was interpreted in terms of the invariant structure of the inertia tensor about the wrist.

**Keywords** Psychophysiology · Heaviness perception · Joint kinematics · EMG · PCA

## Introduction

Until recently, the roles of muscle activity and lifting kinematics in weight perception were investigated separately (Hagberg 1981; De Morree et al. 2012; Lippold 1952; Streit et al. 2007a, b). To accommodate the fact that a single object may be lifted with a variety of muscular forces at a variety of speeds without altering the perception of heaviness, Waddell et al. (2016) investigated the roles of muscle activity and lifting kinematics in combination. Consistent with Newton's second law—stating that force equals mass times acceleration—perceived heaviness was hypothesized to be function of the ratio of the electromyogram EMG of the biceps brachii to the peak acceleration of the elbow during unilateral metronome-paced elbow flexion lifts. The psychophysiological mechanism for perceiving heaviness is not muscle activity alone, but, rather, the amount of muscle activity required to generate a given acceleration. This same result has also been shown across elbow lifts of varying speeds. In many lifts, though, multiple joints and multiple muscles are engaged simultaneously. The goal of the present study is to investigate the roles of multiple muscles (not just the prime movers) and multiple joint accelerations across different lifts.

## Muscles and movement

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

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that the perceived heaviness 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 Morree et al. 2012). In Hagberg (1981), EMG increased with mass during shoulder forward flexion movements with handheld weights; EMG in this study also correlated with measures of load, torque, and perceived exertion. De Morree et 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) all correlated with the mass of the lifted weights. These studies identify a psychophysiological mechanism for heaviness perception in which the perception is a function of muscle activity as a proxy for force.

The previous discussion has shown that perceived heaviness is a function of lifting kinetics—or forces. Perceived heaviness is also a function of lifting kinematics—that is, how the object appears to move (Streit et al. 2007a, b). In these studies, 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. Streit and colleagues interpreted these findings using Newton's second law of motion by noting that an object that moves more slowly in response to a given force will, according to this law relating mass and force to acceleration, necessarily have a greater mass (Streit et al. 2007a, b). However, the forces applied and the muscle activity employed were not measured.

In the research reviewed above, the contributions of EMG and acceleration to perceived heaviness were studied separately. The contributions of each could be interpreted in terms of Newton's second law of motion on the assumption that the other variable was held constant (a common experimental control; De Morree et al. 2012; Streit et al. 2007a, b). That assumption is not necessary, though. Waddell et al. (2016) investigated the combined effects of muscle activity and lifting kinematics by recording EMG, acceleration, and perceived heaviness together. Participants lifted objects that varied in mass and volume using paced unilateral elbow flexion lifts. Both the EMG signal from the biceps brachii muscle and the angular acceleration about the elbow were recorded. Results showed that perceived heaviness scaled to a ratio of EMG to angular acceleration in the following psychophysiological power function:

$$\text{Perceived heaviness} = 10^{0.38}\frac{\text{EMG}^{0.86}}{\text{Acceleration}^{0.65}}. \tag{1}$$

Perceived heaviness is not a function of forces or acceleration separately. Rather, it appears that perceived heaviness is a function of the amount of force required to generate a given acceleration. Extended this finding by having participants lift objects at a variety of speeds, both faster and slower than their preferred. Across this variability in acceleration and EMG, perceived heaviness was unchanged and continued to scale to the ratio of EMG to acceleration.

## Perceived heaviness and the inertia tensor

The research described above supports a psychophysiological mechanism in which perceived heaviness is a function of both the muscle activity and kinematics associated with lifting. Ultimately, though, the goal is to explain the psychophysical connection between perception, action, and some feature in the physical world. For heaviness perception, one might presume that this connection would be between perceived heaviness and mass. However, heaviness perception is not a function of mass alone. This is most evident in the common size-weight illusion in which larger objects feel lighter than smaller objects with the same mass (Amazeen and Turvey 1996; Stevens and Rubin 1970; Dresslar 1894). The physical property for perceived heaviness must be something other than mass. Several studies investigated possible object-based physical properties such as shape (Dresslar 1894) and density (Harshfield and DeHardt 1970; Stevens and Rubin 1970).

Amazeen and Turvey (1996) investigated another physical property—rotational inertia—that was not a property of the object alone, but, rather, a property of the object and the forces and movements being used to lift that object. Rotational inertia is the resistance that the object presents to the rotational forces of the limbs (Amazeen and Turvey 1996; Winter 2009; Fitzpatrick et al. 1994). It can be understood in terms of the rotational version of Newton's second law,

$$\tau = I \cdot \dot{\omega}, \tag{2}$$

where $\tau$ 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. The reason for considering rotational properties is that limb movements are made about a joint and are, therefore, rotational. Using a reanalysis of Stevens and Rubin (1970) along with a series of experiments manipulating mass, size, torque, and mass distribution, Amazeen and Turvey (1996) demonstrated that weight perception and the size-weight illusion were psychophysical functions of an object's rotational inertia. This basic finding has been confirmed across ages (Kloos and Amazeen 2002), modalities (Amazeen 2014; Amazeen and

Jarrett 2003), and styles of lifting (Amazeen et al. 2011). By referring to torque as rotational force, we are suggesting that joint torque should relate to rotational force in these lifting tasks. This is in fact the case—in force perception tasks where lifting is not required, perceptions of force were related to torque in both the wrist (Sanes and Shadmehr 1995) and the whole arm (Toma and Lacquaniti 2016).

Heaviness is only one of many properties perceived through rotational inertia. Research has shown that rotational inertia is the basis for perceiving object length (Cabe 2010; Pagano and Cabe 2003; Stroop et al. 2000), width (Turvey et al. 1998; Carello and Turvey 2004), shape (Takamuku et al. 2008), and orientation (Pagano and Turvey 1992; Turvey et al. 1992). The role of rotational inertia in tool usage has been explored in several contexts (Headrick et al. 2012; Hove et al. 2006; Kim et al. 2013) including the action capabilities, or affordances (Gibson 1979/2014), of tools (Carello 2004; Harrison et al. 2011; Wagman and Shockley 2011).

There is a common theme running through the psychophysiological and psychophysical research on muscle activity, lifting kinematics, and rotational inertia: the perception of heaviness is a function of how an object responds to the forces used in lifting. The psychophysiological studies of De Morree et al. (2012), and Waddell et al. (2016) all focused on the role of the biceps brachii; Hagberg (1981) included the trapezius and deltoid muscles. Psychophysical research has shown that rotational inertia is used equivalently across different joints and effectors (Carello et al. 1998; Hajnal et al. 2007a, b; Pagano et al. 1993; Palatinus et al. 2014; Wagman et al. 2017), and that perceived force is scaled relative to the muscle group being used (Jones 2003). It is important, then, to identify whether the psychophysiological mechanism proposed by Waddell et al. (2016) is similarly equivalent across lifts using different muscles.

## Current experiment

This experiment examined the roles of EMG and joint kinematics in perceiving heaviness across three different arm lifts. The goal was to determine if these effects changed as the muscles and joints serving as prime movers changed. Participants in this study used three different arm lifts—about the shoulder, elbow, and wrist—to judge the heaviness of objects. EMG from the anterior deltoid, biceps brachii, and forearm flexors were recorded along with the angular accelerations about each joint. Principal components analysis (PCA) of both EMG and acceleration was used to identify which muscles and joints were the primary contributors to each lift (see Charoenpanicha et al. 2013). These primary contributors were used to generate psychophysiological power functions of the form in Eq. 1. It was hypothesized that perceived heaviness would scale to a ratio of muscle activity to peak acceleration. Specifically, that ratio would be indicated by a psychophysiological power function with a positive exponent for EMG and a negative exponent for acceleration.

## Methods

### 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. 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 but were otherwise identical, and reported perceived heaviness compared to a standard. There were five levels of Mass and three lifts (shoulder, elbow, and wrist), resulting in a 5 (Mass) × 3 (Lift) design. Peak angular acceleration about each joint and the root mean square (rms) 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 (210, 340, 470, 600, and 730 g). The standard had a Mass of 500 g. All stimuli had a volume of 970 $\text{cm}^3$. Each stimulus had a length-to-width ratio of 1.7. EMG of the muscle of interest was recorded at 1000 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 was 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. Lifting kinematics were recorded using a Northern Digital Optotrak 3020 motion tracking system. This system recorded the three-dimensional positions of infrared-light-emitting diodes (IREDs) at a sampling rate of 1000 Hz. Movement data were recorded from IREDs attached to the shoulder, elbow, wrist, and object.

## 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. 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 were instructed to report a number quantifying the perceived heaviness of the objects relative to a standard, which was given an arbitrary heaviness of 100. Participants were informed that the numerical estimations could be as high or low as they wanted—as long as they accurately reflected how heavy the objects felt compared to the 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.

## Data analysis

EMG values were calculated from muscle activity of the forearm flexors, biceps brachii, and anterior deltoid muscles. These data were filtered with a 20–500 Hz Butterworth filter and then fully rectified (Criswell 2011). The EMG (in volts) was calculated from the beginning to end of each lift. The rms EMG during the upward portion of each lift was recorded as the index of muscular effort and proxy for muscular force. 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. These data were 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 maximum angular acceleration during the upward portion of each lift was recorded as the measure of lifting acceleration. Two-way repeated measures analyses of variance (ANOVAs) were conducted on perceived heaviness, EMG, and angular acceleration as a function of mass and lift.

PCA was used to determine the role of each muscle and movement during each lift. PCA 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 et al. 2004). PCA has been used to identify the kinematic and kinetic variables used in movements such as jumping, (Charoenpanicha et al. 2013; Kollias et al. 2001), throwing (Tripp et al. 2006) dance (Hollands et al. 2004), and more (Boyer et al. 2014; Lee et al. 2009; Pinter et al. 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 from each muscle and from each the angular acceleration about each joint. The muscle whose activity loaded on the first component most frequently across participants was identified as the primary contributor of muscle activity. Likewise, the joint whose angular acceleration loaded on the first component most frequently across participants was identified as the primary contributor of acceleration. The psychophysiological power functions were then calculated using the data from these primary contributors.

To identify the underlying psychophysiological 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 were divided 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 2011). 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 lifts should be positive and the exponent on angular acceleration should be negative.

## Results

### Perceived heaviness

Figure 1 shows mean perceived heaviness as a function of Mass and Lift. As expected, perceived heaviness increased as Mass increased. As Mass increased from 210 to 730 g, perceived heaviness increased from 27 to 202. This main effect of Mass was significant, $F(4,72) = 119.30$, $p < .05$, and $\eta_p^2 = .87$. 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.

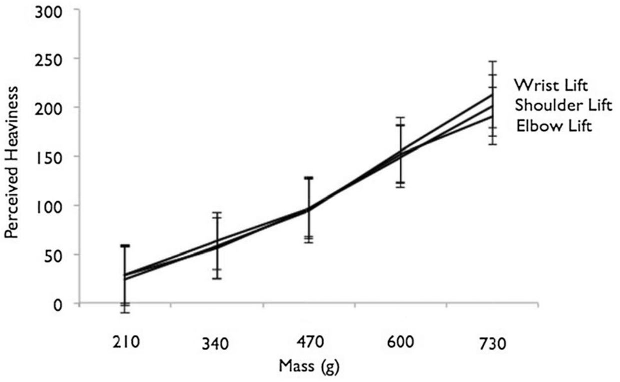

**Fig. 1** Mean perceived heaviness ratings of all stimuli for all lifts relative to a standard of 100

### Muscle activity

*Anterior deltoid*

Figure 2a shows mean rms EMG of the anterior deltoid as a function of Mass and Lift. As Mass increased from 210 to 730 g, rms EMG of the anterior deltoid increased from .25 to .31 V. The main effect of Mass was significant, $F(4,72) = 12.48$, $p < .05$, and $\eta_p^2 = .41$. The mean rms EMG of the anterior deltoid was .62 V during a shoulder lift, .18 V during an elbow lift, and .05 V during a wrist lift. The main effect of Lift was significant, $F(2,36) = 25.68$, $p < .05$, and $\eta_p^2 = .58$. These main effects were accompanied by a significant interaction of Mass and Lift, $F(8,144) = 6.14$, $p < .05$, and $\eta_p^2 = .25$. Simple effects tests revealed that as Mass increased, rms EMG of the anterior deltoid increased significantly during shoulder

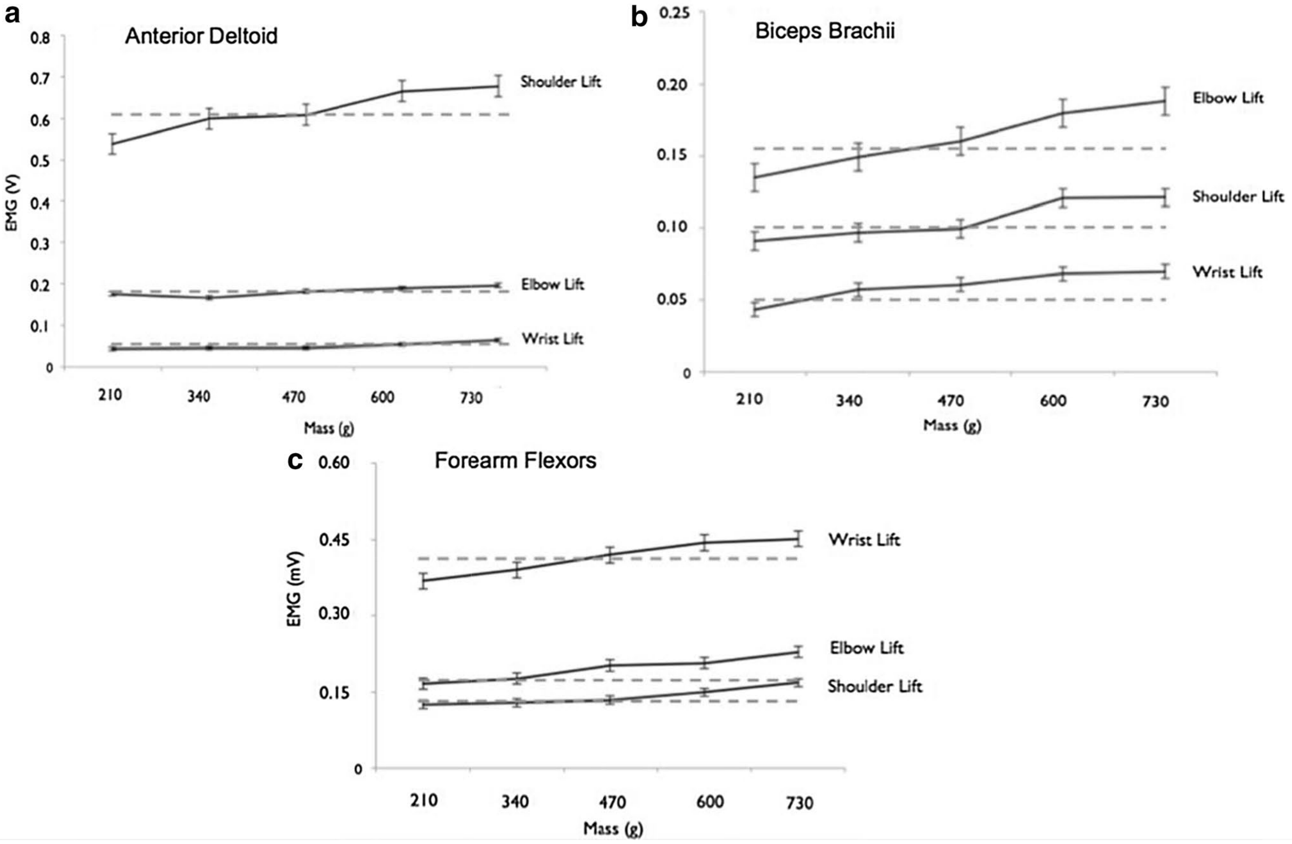

**Fig. 2** Mean rms EMG in volts ($V$) recorded from the **a** anterior deltoid, **b** biceps brachii, and **c** forearm flexors during shoulder, elbow, and wrist lifts. *Dotted lines* show mean values

lifts, $F(4{,}72) = 11.672$, $p < .05$, and $\eta_p^2 = .6$; and wrist lifts, $F(4{,}72) = 2.92$, $p < .05$, and $\eta_p^2 = .14$, but not during elbow lifts, $F(4{,}72) = 1.30$, $p > .05$, $\eta_p^2 = .07$.

### *Biceps brachii*

Figure 2b 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 .08 to .12 V. The main effect of Mass was significant, $F(4{,}72) = 28.73$, $p < .05$, and $\eta_p^2 = .61$. The mean rms EMG of the biceps brachii was .10 V during a shoulder lift, .16 V during an elbow lift, and .05 V during a wrist lift. The main effect of Lift was significant, $F(2{,}36) = 31.73$, $p < .05$, and $\eta_p^2 = .64$. The main effects were accompanied by a significant interaction of mass and lift, $F(8{,}144) = 2.78$, $= p < .05$, and $\eta_\text{p}^2 = .13$. Pairwise comparisons revealed the sources of the interaction to be significant differences between four pairs of adjacent masses (470 vs. 600 g during shoulder lifts, $t(18) = 2.86$, $p < .05$; 210 vs. 340 g during elbow lifts, $t(18) = 3.13$, $p < .05$; 470 g vs. 600 g during elbow lifts, $t(18) = 4.55$, $p < .05$; and 210 vs. 340 g during wrist lifts, $t(18) = 3.12$, $p < .05$), while all other comparisons were not significant, all *t*s < 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 *F*s > 7.71, all *p*s < .05).

### *Forearm flexors*

Figure 2 (c) 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 .21 to .29 V. The main effect of Mass was significant, $F(4{,}72) = 19.89$, $p < .05$, and $\eta_p^2 = .52$. The mean rms EMG of the forearm flexors was .14 V during a shoulder lift, .19 V during an elbow lift, and .41 V during a wrist lift. The main effect of Lift was significant, $F(2{,}36) = 55.78$, $p < .05$, and $\eta_p^2 = .76$. The main effects were accompanied by a significant interaction of Mass and Lift, $F(8{,}144) = 2.14$, $= p < .05$, and $\eta_p^2 = .11$. Pairwise comparisons revealed the sources of the interaction to be significant differences between six pairs of adjacent masses (470 vs. 600 g during shoulder lifts, $t(18) = 2.67$, $p < .05$; 600 g vs. 730 g during shoulder lifts, $t(18) = 2.40$, $p < .05$; 340 g vs. 470 g during elbow lifts, $t(18) = 3.33$, $p < .05$; 600 vs. 730 g during elbow lifts, $t(18) = 2.20$, $p < .05$; 340 vs. 470 g during wrist lifts, $t(18) = 2.26$, $p < .05$; 470 g vs. 600 g 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 3a 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 .011° to .010 °/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 .024°, .0057 deg/ms$^2$ during an elbow lift, and .0033 deg/ms$^2$ during a wrist lift. The main effect of Lift was significant, $F(2{,}36) = 221.73$, $p < .05$, and $\eta_p^2 = .92$. Simple effects tests revealed that 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 3b 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 .024 to .021 deg/ms$^2$. The main effect of Mass was significant, $F(4{,}72) = 3.83$, $p < .05$, and $\eta_p^2 = .16$. The mean peak angular acceleration of the elbow was .018 deg/ms$^2$ during a shoulder lift, .034 deg/ms$^2$ during an elbow lift, and .013 deg/ms$^2$ during a wrist lift. The main effect of Lift was significant, $F(2{,}36) = 28.89$, $p < .05$, and $\eta_p^2 = .62$. Simple effects tests revealed that 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 3c 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 .042 ° to .036 deg/ms$^2$. The main effect of Mass was not significant, $F(4{,}72) = 1.78$, ns. The mean peak angular acceleration of the wrist was .023 deg/ms$^2$ during a shoulder lift, .026 deg/ms$^2$ during an elbow lift, and .067 deg/ms$^2$ during a wrist lift. The main effect of Lift was significant, $F(2{,}36) = 48.37$, $p < .05$, and $\eta_p^2 = .73$. Simple effects tests revealed that acceleration during a wrist lift differed significantly from elbow lifts, $F(1{,}18) = 101.31$, $p < .05$, and $\eta_p^2 = .85$, and shoulder lifts, $F(1{,}18) = 56.48$, $p < .05$, and $\eta_p^2 = .76$. However, wrist acceleration did not differ between elbow and shoulder lifts, $F(1{,}18) = .26$, ns. There was a significant

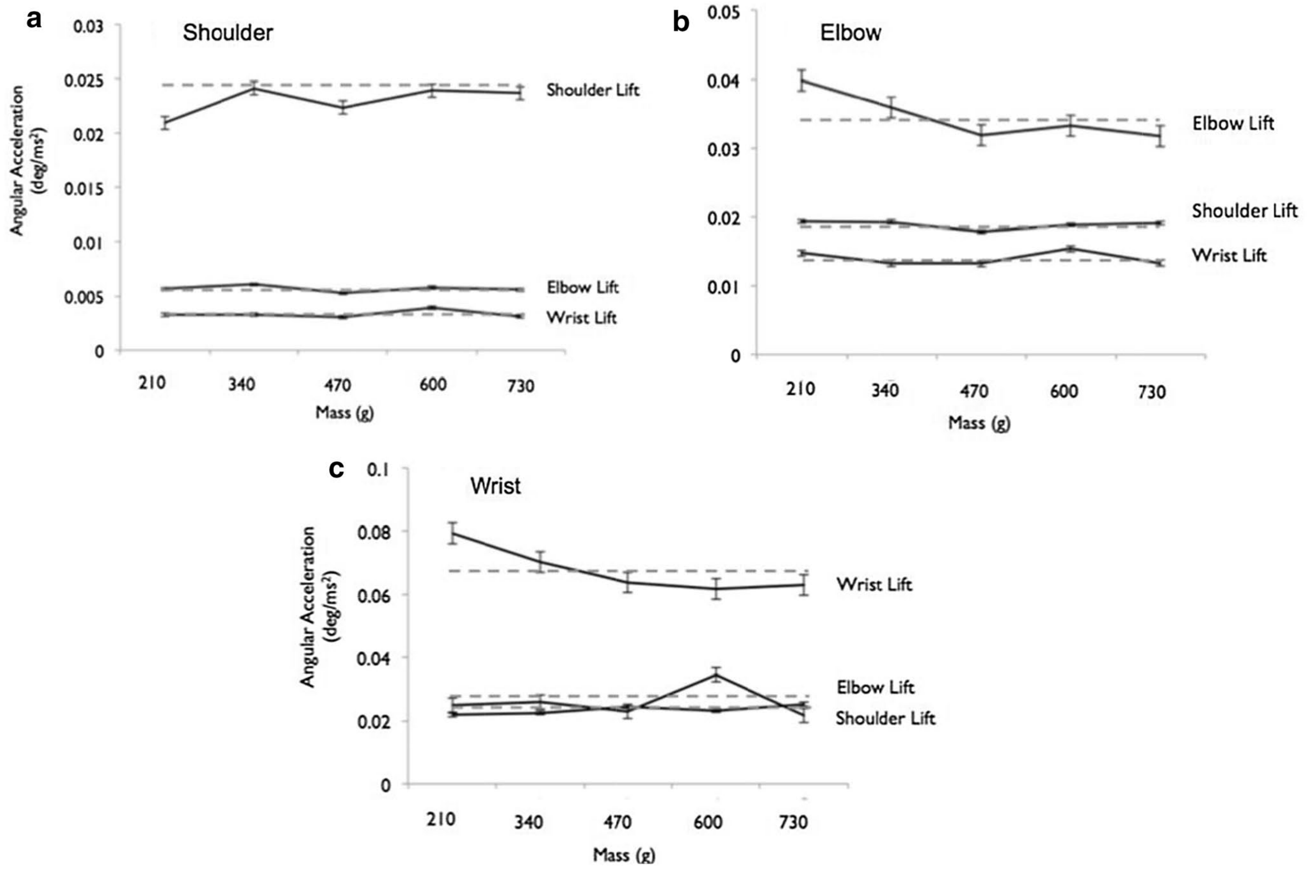

**Fig. 3** Mean peak angular acceleration (deg/ms$^2$) recorded from the **a** shoulder, **b** elbow, and **c** wrist during shoulder, elbow, and wrist lifts. *Dotted lines* show mean values

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 Fig. 4a–c. 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 Fig. 4d–f. 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.

## Psychophysiological power functions

The 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 results of the PCA determined which rms EMG and angular acceleration values were used to generate each psychophysiological power function (see Fig. 5 for the values of EMG and Angular Acceleration exponents across all lifts).

### *Shoulder lift*

Log perceived heaviness was regressed onto log rms EMG of the forearm flexors and log peak angular acceleration of the shoulder during shoulder lifts. The overall regression was significant, $R^2 = .16$, $F(2,272) = 20.57$ $p < .05$. The regression revealed a positive exponent for EMG with a value of 1.70, $t = 7.13$, $p < .05$; and a negative exponent for

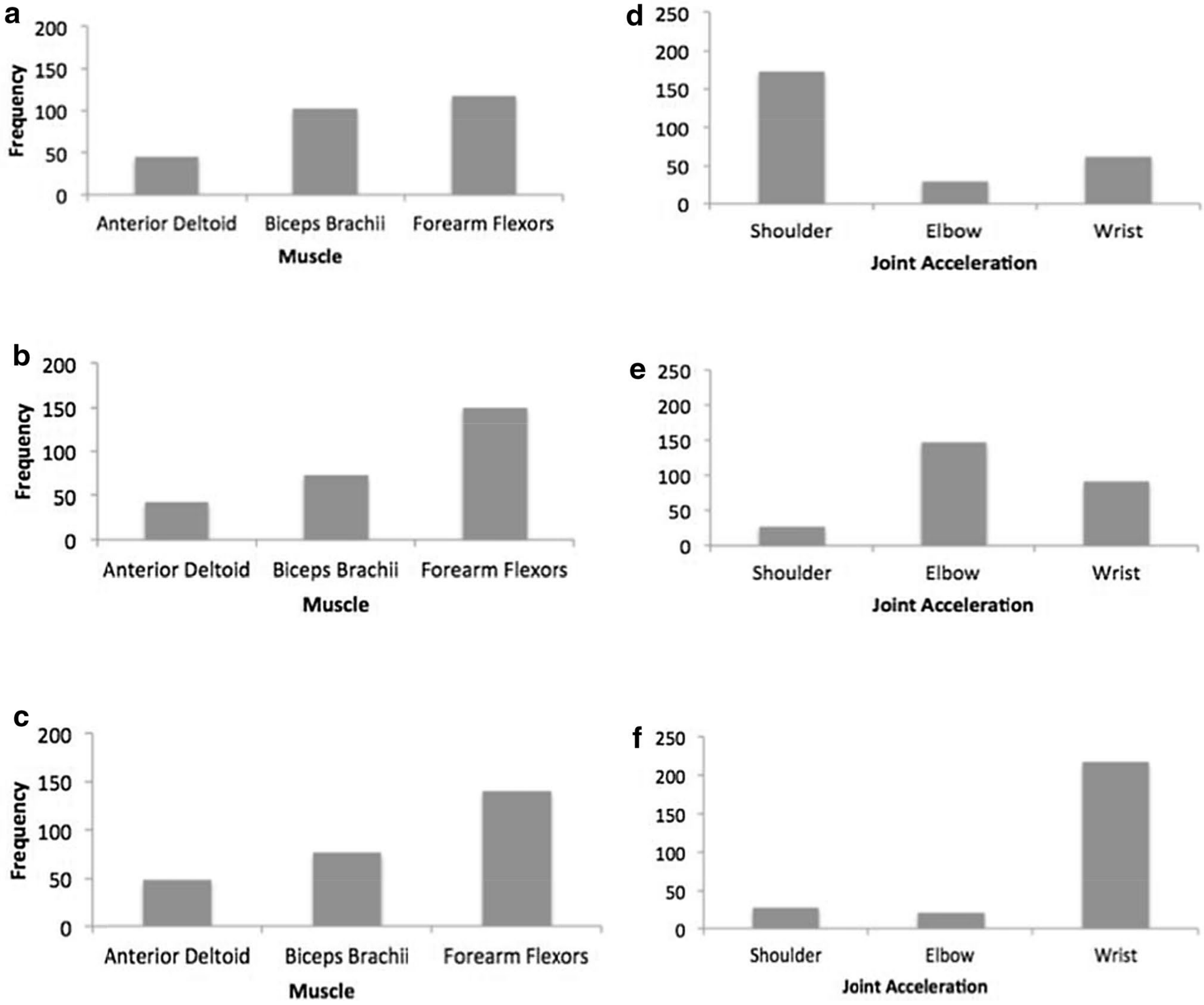

**Fig. 4** **a** Principal muscle sources revealed by the PCA analysis during shoulder lifts, **b** elbow lifts, and **c** wrist lifts. **d** Principal acceleration sources revealed by the PCA analysis during shoulder lifts, **b** elbow lifts, and **c** wrist lifts

Acceleration with a value of −.19, $t = -1.70$, and $p < .05$. 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$^{-.19}$.

*Elbow lift*

Log perceived heaviness was regressed onto log rms EMG of the forearm flexors and log peak angular acceleration of the elbow during elbow lifts. The overall regression was significant, $R^2 = .17$, $F(2{,}272) = 28.63$ $p < .05$. The regression revealed a positive exponent for EMG with a value of 1.44, $t = 7.20$, and $p < .05$; and a negative exponent for Acceleration with a value of −.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$^{-.10}$.

*Wrist lift*

Log perceived heaviness was regressed onto log rms EMG of the forearm flexors and log angular acceleration of the wrist during wrist lifts. The overall regression was significant, $R^2 = .13$, $F(2{,}272) = 20.55$ $p < .05$. The regression revealed a positive exponent for EMG with a value of 1.31, $t = 5.85$, and $p < .05$; and a negative exponent for Acceleration with a value of −.65, $t = -5.20$, and $p < .05$. Using the resulting coefficients as exponents resulted in the following psychophysiological power function for shoulder lifts: Perceived

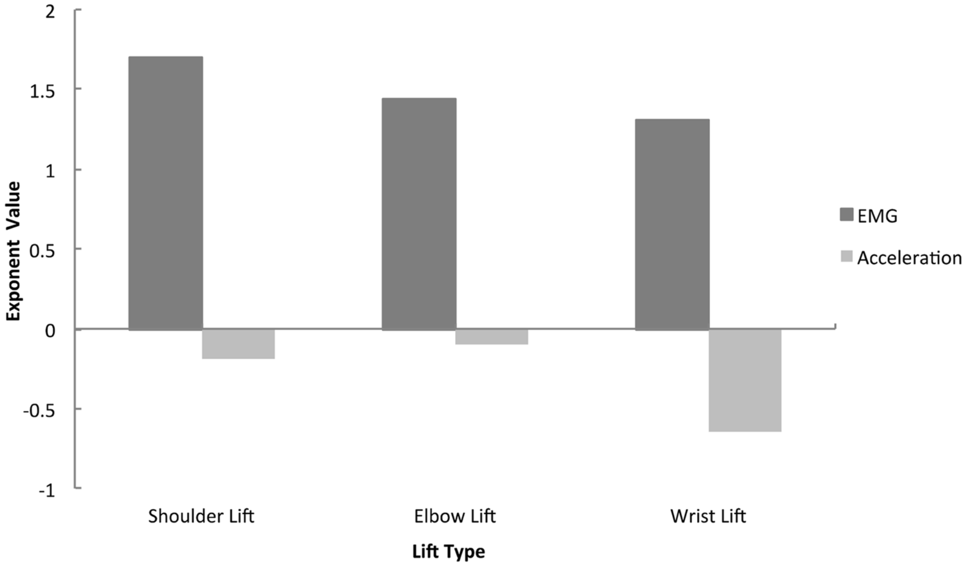

**Fig. 5** Exponents resulting from the PCA regression using forearm flexor EMG and the angular acceleration from each lift's corresponding joint

Heaviness = $10^{3.06}$ × Forearm Flexors rms $\text{EMG}^{1.44}$ × Wrist $\text{Acceleration}^{-.65}$. It is important to note that while the variance in perceived heaviness accounted for by these models may not be large, the measures used in the models (muscle activities and angular accelerations) are serving as proxies for mass and acceleration, and, therefore, will not account for as much variance (see Waddell et al. 2016).

## Discussion

This study investigated a psychophysiological mechanism for perceiving heaviness across different muscles and different lifts. Participants lifted objects that varied in mass with shoulder, elbow, and forearm lifts, while muscle activity and joint kinematics from several locations on the arm were recorded. By performing PCA on the muscle activity and movement, we showed that corresponding lift accelerations and forearm flexor muscle activity were the most relevant for perceiving heaviness. Regressing perceived heaviness ratings onto these measures revealed that across all three lifts, perceived heaviness was a function of the ratio of muscle activity to joint acceleration. This finding is similar to those found during elbow lifts (Waddell et al. 2016). These findings suggest that the way in which muscle activity and movement combine for perceived heaviness is similar across muscles and movements. This is supported by the biotensegrity hypothesis (Turvey and Fonseca 2014), which accounts for how haptic perceptual processes are distributed by considering the body a tensegrity system (also see Palatinus et al. 2011; Wagman et al. 2017). Furthermore, results from the PCA provide further evidence that haptic perception is tied to dynamics calculated about the wrist.

### Different muscles, same perception

We perform countless lifts everyday to control objects and, therefore, perceive heaviness. An elbow flexion may be used to lift a bag, while a forearm flexion may be used to lift a pencil. In each lift, the prime mover changes—it is the bicep when lifting the bag and the forearm flexors when lifting the pencil. The current experiment asked whether the muscle most relevant for heaviness perception changes in a similar way. To do this, the roles of different muscles and joints in perceiving heaviness were explored across three different arm lifts. Principal component analysis was performed on the muscle activity and accelerations 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. 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.

PCA 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. These results suggest that the forearm flexor and angular acceleration of the corresponding joint were the most relevant for heaviness perception.

While the roles of each muscle were the same across lifts, the roles of each joint's movements changed across lifts. This is consistent with research that has shown how movements generate the information used to perceive heaviness (Amazeen 2014; Greer 1989; Streit et al. 2007a, b). 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) experienced 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 flexors were the most relevant muscles 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. Despite the fact that the prime movers changed, the forearm flexors loaded most frequently on the first component across all lifts—it was the most important muscle for heaviness perception. This finding is important in the context of the psychophysics related to rotational inertia. Specifically, the psychophysiological function suggests that forearm flexors are involved in perception, because they are the muscles tied to the invariant properties of the object. Investigating the exponents from the psychophysiological power function (see Fig. 5) shows that the exponent for acceleration during a wrist lift is larger in absolute value than the acceleration exponents during the shoulder and elbow lifts. In these types of psychophysical functions, the absolute value of exponents can be interpreted as related to the saliency of the stimuli for perception (see Stevens 1957, 1960). If we remember that the accelerations used in these regressions were the corresponding joint accelerations, it reveals that the forearm flexor muscle activity was salient across all lifts and wrist acceleration seemed to be salient—all of the wrist measures were salient across lifts, which has interesting implications for rotational inertia.

There is evidence to show that haptic perception is tied to the rotational inertia about the wrist (Pagano et al. 1993). As previously discussed, limb movements are rotational about a joint. Any change in the joint about which rotational inertia is calculated will change its value, because rotational inertia is a function of both mass and its distance from the point of rotation. Pagano et al. (1993) investigated whether participants used the rotational inertia about different joints across different movements. Participants wielded rods about different points of rotation (joints) and reported 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 rotational inertia computed about the wrist. This is important, because only the rotational inertia about the wrist remains invariant across movements (because that is the only joint that remains a fixed distance from the object). Studies investigating the role of rotational inertia in weight perception typically use rotational inertia calculated about the wrist (e.g., Amazeen and Turvey 1996; Kingma et al. 2004; Streit et al. 2007b). Furthermore, a recent study sought to investigate the link between motor output and perception by measuring eight arm muscles, while participants performed a force judgment task. Not only did muscle activity predict perceptual judgments, but also individual differences in those judgments were correlated with muscle activity and joint torque (Toma and Lacquaniti 2016). In light of this, it is not surprising to find heaviness perception relies mainly on muscle activity from the forearm flexor. Several studies have also investigated length perception of objects wielded by other parts of the body, such as the head, torso, and foot (see Hajnal et al. 2007b; Wagman et al. 2017; Palatinus et al. 2014). These show that an inertial model of object property perception such as heaviness perception (like the one used here) extends to those perceptions. Further research is needed though to see whether the claim made in the current investigation about the importance of the proximal joint (and the muscle and movement evidence to support this claim) can be extended to other parts of the body.

## Conclusions

Perceived heaviness is function of muscle activity and movement combined (Waddell et al. 2016). The current study extends this finding by showing that these effects are similar across different lifts; in all cases, perceived heaviness was a psychophysiological function of the ratio of muscle activity to joint acceleration. However, PCA revealed that the specific roles of each muscle and joint were not identical across lifts. While the angular accelerations from primary lifting joint were most relevant to perceiving heaviness, the same was not true for muscle activity. Across all three lifts, the forearm flexor was most relevant for this perception. This may be because the stimulus property for perceived heaviness—rotational inertia—is only invariant about this joint.

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