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RESEARCH ARTICLE

# Muscular effort differentially mediates perception of heaviness and length via dynamic touch

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## Abstract

Our ability to perceive properties of handheld objects (e.g., heaviness, orientation, length, width, and shape) by wielding via dynamic touch is crucial for tooling and other forms of object manipulation—activities that are the basis of much human experience. Here, we investigated how muscular effort mediates perception of heaviness and length via dynamic touch. Twelve participants wielded nine occluded elongated objects of distinct moments of inertia and reported their perceptual judgments of heaviness and length. We measured the electromyography (EMG) activity of the participants' biceps brachii, flexor carpi radialis, and flexor carpi ulnaris muscles during wielding. Distinct single-valued functions of the eigenvalues $I_1$ and $I_3$ of the inertial tensor, $I$, closely predicted perceived heaviness and perceived length of the wielded objects. Perceived heaviness showed a direct and linear relationship with EMG activity of biceps brachii, flexor carpi radialis, and flexor carpi ulnaris. However, while perceived length showed a very weak relationship with EMG activity of biceps brachii, we found no association between perceived length and EMG activity of flexor carpi radialis and flexor carpi ulnaris. Our findings indicate that muscular effort contributes directly to perception of heaviness, but likely only serves as a medium for perception of length. While the same physical variable—i.e., the moment of inertia—provides the informational support for perception of heaviness and length, distinct psychophysiological processes underlie perception of heaviness and length via dynamic touch.

**Keywords** Effortful touch · Exteroception · Heaviness perception · Length perception · Moment of inertia

## Introduction

"The hand can become a claw, a fist, a horn or spear or sword or any other weapon or tool. It can be everything because it has the ability to grasp anything or hold anything" wrote Aristotle in The Animal Parts (IV, 10). This statement refers to a remarkable capability of humans that is not yet fully understood: the capacity to extend the sense of touch into the world, beyond the body, so as to perceive, for example, an object's mass, orientation, length, width, shape and other qualities that specify the functional affordances of that object. This sub-system of the haptic perceptual system, which is referred to as dynamic (or effortful) touch, entails all acts of object manipulation and tooling that form the basis of much human experience (see reviews by Carello and Turvey 2000; Turvey and Carello 2011). The various complexities of the hand–object dyadic system are more readily engaged in wielding than understood conceptually. In this study, we build on a large body of scientific literature on dynamic touch by addressing the question: how do the interplay of specific features of the environment and the perceiver's body give rise to functionally appropriate perceptual judgments?

Dynamic touch involves the detection of three moments that quantify how an object's mass is distributed in space: mass, the static moment, and the moment of inertia. These quantities can be easily envisioned through the following example: take any object, divide it into millions of parts, leaving it in its original shape. Mass is the moment that is obtained by simply adding up the individual mass of each part. The static moment is obtained first by measuring how

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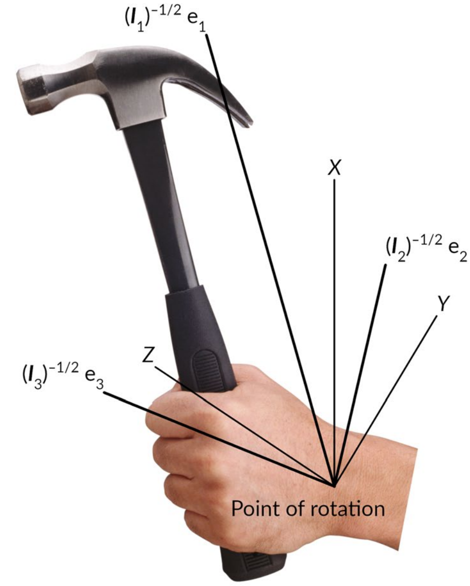
far each part is from a given axis, multiplying that by the mass of each part, and summing all the mass × distance products. The final moment is the moment of inertia, which is calculated similar to the static moment with the slight change that it involves multiplying the mass of each part by distance squared. The three moments together determine the joint torque, $\tau_{\text{joint}}$, required to initiate the rotational motion of the object about a joint:

$$\tau_{\text{joint}} = I\omega + mgr \cdot \cos(\theta), \tag{1}$$

where $m$ is the mass of the object, $r$ is the radius of gyration about the wrist, $g$ is acceleration due to gravity, and $\theta$ is the angle of the object relative to the horizontal plane. The formula mgr cos($\theta$) represents the static torque, $\tau_{\text{static}}$, due to the object's weight; here $mgr$ represents the invariant static moment, $\mu$. $I$ is the moment of inertia and $\omega$ is the angular acceleration. $I\omega$ represents the dynamic torque, $\tau_{\text{dynamic}}$, due to the object's rotational motion. Cyclic movements during wielding the object allow the detection of the moment of inertia (Fitzpatrick et al. 1994).

Understanding the implications of the moment of inertia for perception via dynamic touch requires elaboration. A handheld object freely wielded is of three dimensions, that is, it is rotated about each of three axes: one vertical, one horizontal, and one in depth. The moment of inertia about each axis can be calculated, capturing the object's resistance to rotational acceleration: the degree to which it resists being rotated back and forth, up and down, or twisted. The moment of inertia is represented by a 3 × 3 matrix—the "inertia tensor" of the hand-object system (Fig. 1). The eigenvectors $e_1$, $e_2$, and $e_3$ of $I$ specify the orientation of the object relative to the hand (Pagano and Turvey 1992; Turvey et al. 1992). The eigenvalues $I_1$, $I_2$, and $I_3$ specify the resistance to angular acceleration about the symmetry axes of wielded objects along each of these dimensions. Accordingly, distinct combinations of the largest and the smallest eigenvalues, $I_1$ and $I_3$, specify the length and width of wielded objects (Fitzpatrick et al. 1994; Turvey et al. 1998), while the ratio of $I_1$ and $I_3$ specifies the distribution of mass and thereby the shape of wielded objects (Burton et al. 1990). $I_1$, $I_2$, and $I_3$ together specify the heaviness of wielded objects (Amazeen 1999; Carello et al. 1999). Additionally, the influence of an object's physical dimensions on perception of its heaviness depends on specific patterns of $I_1$, $I_2$, and $I_3$ (Amazeen and Turvey 1996).

The applied muscular effort provides for the psychophysiological processes that enable the detection of the moment of inertia, acting as a medium through which functionally relevant perceptual judgments are derived. Previous findings indicate that although some amount of muscular effort is required for perception of length, this is not, after a minimum threshold, directly related to judgments of length. For instance, people can accurately perceive the length of rods




| Component of $I$ | Property of object |
|---|---|
| $e_1$, $e_2$, & $e_3$ | Orientation |
| $I_1$ & $I_3$ | Length & Width |
| $I_1$, $I_2$, & $I_3$ | Shape |

**Fig. 1** Eigenvalues ($I_1$, $I_2$, and $I_3$) and eigenvectors ($e_1$, $e_2$, and $e_3$) of the inertial tensor of the hand–object system (the origin of the coordinate system lies at a point in the wrist). The components of $I$ and the properties of the objects they specify are tabulated below

supported at the other end by touching them with minimal effort (Burton and Turvey 1990; Carello et al. 1992). In previous work, comparing perception of length by wielding objects in air and water, participants exerted greater muscular effort in water, but perceived length remained constant across the two media (Pagano and Donahue 1999; Pagano and Cabe 2003; Mangalam et al. 2017, 2018). Likewise, perception of length remains constant across low and high wielding speeds (Streit et al. 2007a, b); but wielding at higher speeds requires more muscular effort. Nonetheless, this was found to be unrelated to judgments of length. Thus, perception of length is not based on muscular effort alone. By contrast, evidence supports an interpretation of perception of heaviness as being a function of muscular effort. Intuitively, objects feel heavier primarily because they are lifted with greater force than lighter-feeling objects. Recent findings indicate that participants' judgments of heaviness are determined by the [specifically scaled] ratio of muscular effort to lifting acceleration (Waddell et al. 2016; Waddell and Amazeen 2017, 2018a, b). Therefore, the biomechanical implications of heaviness and length are very distinct; since muscular effort is closely related to lifting and supporting an object, and lifting and supporting an object is closely associated with feelings of heaviness, we can expect a more direct role of muscular effort in perception of heaviness than in perception of length.

Here, we examined whether muscular effort contributes more directly to perception of heaviness than to perception of length. Twelve participants individually lifted and wielded occluded objects with distinct values of the moment of inertia and report their judgments of heaviness and length. We first established that the moment of inertia serves as the specifying variable for perception of heaviness and length via dynamic touch, and then identified the relationships between muscular effort and judgments of heaviness and length. Because of the inherent redundancy in the neuromuscular system (Bernstein 1967), no one-to-one relationship exists between muscular activity and joint torques, but muscle activity is still closely related to joint torques (Shin et al. 2009). Accordingly, we recorded EMG activity in biceps brachii, flexor carpi radialis, and flexor carpi ulnaris muscles of the participants. First, given that lifting and wielding an object necessitates countering the joint torque exerted by that object, we anticipated that EMG activity of each muscle would closely predict perceived heaviness. Second, assuming that any varying amount of muscular effort above a minimum threshold is adequate to detect the eigenvalues of *I*, irrespective of the magnitude of those eigenvalues, we expected no significant relationship between EMG activity and perceived length.

# Methods

## Participants

Seven adult males and five adult females (mean ± SD age = 23.0 ± 4.3 years, 19–31 years, 10 right-handed, one left-handed) voluntarily participated in the present study. Each participant signed a printed consent form with information about the purposes of the study, the procedures, and the potential risks and benefits of participation. The Institutional Review Board (IRB) at the University of Georgia (Athens, GA, USA) approved the present study.

## Experimental objects

We used nine experimental objects, each consisting of a weighted dowel (length = 75.0 cm, diameter = 1.2 cm) of a particular composition: (1) oak wood, (2) hollow aluminum, and (3) solid aluminum. We attached four, six, and twelve steel rings (inner diameter = 1.4; outer diameter = 3.4 cm; thickness = 0.2 cm; mass = 14 g) to each dowel at 20.0, 40.0, and 60.0 cm, respectively, from its proximal end. To prevent the cutaneous perception of a dowel composition, we enfolded a rubber grip of negligible mass and thickness around the base of each object (length = 15.0 cm). Overall, nine distinct values of the moment of inertia ($I_1$ and $I_3$) were expressed across the nine objects (Table 1).

## Experimental setup and procedure

We tested each participant in a 75–90-min session. In this session, the respective participant performed a total of 27 trials (9 objects × 3 trials/object). We randomized the order of presentation of the 27 trials for each participant.

EMG activities (μV) of biceps brachii, flexor carpi radialis, and flexor carpi ulnaris muscles of each participant's right arm were recorded. The activity of the forearm flexor muscles predominantly contributes to perception via dynamic touch (Waddell and Amazeen 2017). However, since movements about the wrist generate interaction torques about the elbow and shoulder (Hollerbach and Flash 1982), we also measured EMG activity of the biceps brachii muscle. We recorded EMG activity at 1926 Hz using a Delsys Trigno™ wireless EMG system (Delsys Inc., Boston, MA, USA). We attached the sensors parallel to the muscle fibers, on the center of the muscle's belly. We rubbed the

**Table 1** Experimental objects ($n = 9$)

| Object | Dowel | | | Attached rings | | Object parameters | |
|---|---|---|---|---|---|---|---|
| | Composition | Length (cm) | Mass (g) | Mass (g) | Location (cm) | $I_1$ (g cm$^2$) | $I_3$ (g cm$^2$) |
| 1 | Oak wood | 75 | 68 | 168 | 20 | 153,500 | 3220 |
| 2 | Oak wood | 75 | 68 | 84 | 40 | 214,290 | 1500 |
| 3 | Oak wood | 75 | 68 | 56 | 60 | 278,850 | 900 |
| 4 | Hollow aluminum | 75 | 109 | 168 | 20 | 194,720 | 1190 |
| 5 | Hollow aluminum | 75 | 109 | 84 | 40 | 256,450 | 320 |
| 6 | Hollow aluminum | 75 | 109 | 56 | 60 | 321,770 | 660 |
| 7 | Solid aluminum | 75 | 266 | 168 | 20 | 459,850 | 5850 |
| 8 | Solid aluminum | 75 | 266 | 84 | 40 | 521,260 | 3290 |
| 9 | Solid aluminum | 75 | 266 | 56 | 60 | 586,720 | 3110 |

participant's skin with isopropyl alcohol pads before attaching the sensors to reduce skin impedance.

Each participant stood on a designated spot and inserted his/her right hand in a 30-cm slit through a curtain on the right at his/her midriff height (Fig. 2). Before each trial, the participant lifted a reference object that they later used to report perceived mass of the wielded objects. We designated this object an arbitrary mass of 100 (no units). We instructed the participant to assign heaviness values proportionally greater than 100 to objects perceived heavier than the reference object and heaviness values proportionally less than 100 to objects perceived lighter than the reference object. In each trial, the experimenter signaled 'lift' ($t=0$ s), following which the participant grasped and lifted the object. After about 20 s ($t=20$ s), the experimenter signaled 'wield,' following which the participant wielded the object about his/her wrist. After 25 s ($t=45$), the experimenter signaled 'stop,' and the trial ended. The participant reported perceived heaviness of the wielded object (no units) relative to the reference object. Immediately following this, the participant reported perceived length by adjusting the position of a marker by pulling a string on a string-pulley assembly. The experimenter registered perceived length (cm) on a 2.00-m long scale attached to the base of the string-pulley assembly. The readings on the scale were not visible to the participant. We encouraged the participant to take breaks to avoid fatigue.

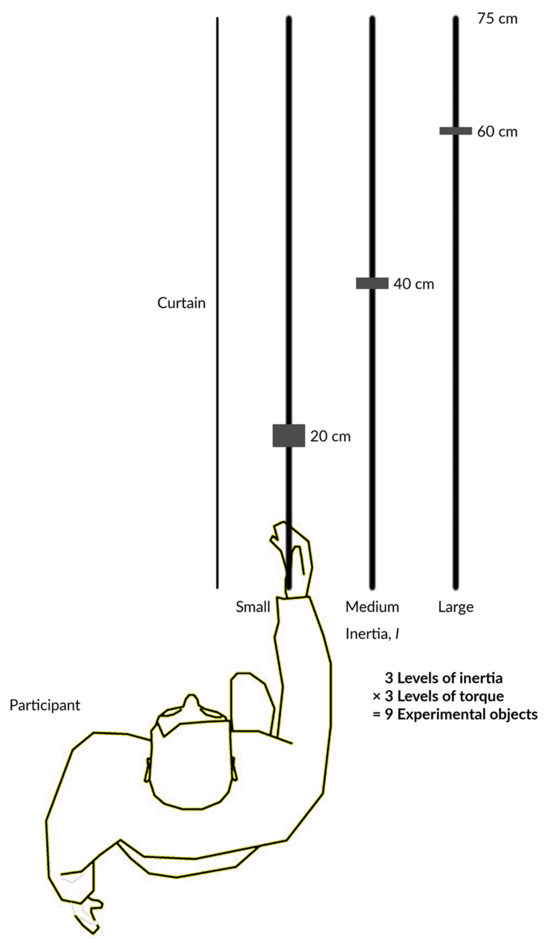



**Fig. 2** Schematic illustration of the experimental objects and the experimental setup (top view)

## Analysis

Twelve participants together constituted 324 trials (12 participants × 9 objects/participant × 3 trials/object) and thus 324 EMG signals for each muscle: biceps brachii, flexor carpi radialis, and flexor carpi ulnaris. We processed all 324 EMG signal using a fourth order, 5 Hz high-pass filter followed by a 4th order, 20 Hz low-pass filter in MATLAB 2018a (MathWorks Inc., Natick, MA, USA), fully rectified all EMG signals and computed the root mean square (RMS) values for all EMG signals. To account for individual variability among the participants due to varying muscle size, skin impedance, and electrode placement, et cetera, we normalized each RMS value for ith participant by first divided it by the mean of all RMS values for that participant to cluster each participant's data around zero, and then multiplying by the grand mean across all participants to cluster each participant's data around the grand mean (cf. Waddell et al. 2016; Waddell and Amazeen 2017). We performed all statistical analyses using linear mixed-effects (LME) models in MATLAB 2018a or linear regressions in SPSS (IBM Inc., Chicago, IL, USA) and considered the outcomes statistically significant at the alpha level of 0.05. We provide complete details of LME models and regressions in Results or Tables 2 and 3.

**Table 2** Outcomes of linear mixed-effects models (perceptual judgements against $I_1$ and $I_3$)

| Variable | $b$ | SE ($b$) | $t_{291/394}$ | $P$ | CI [lower, upper] |
|---|---|---|---|---|---|
| Log$H_{peceived}$* ~ log$I_1$ + log$I_3$ + (1 \| participant) + (1 \| participant: trial) | | | | | |
| (Constant) | − 0.281 | 0.214 | − 1.315 | 0.192 | − 0.706, 0.143 |
| Log$I_1$ | 0.423 | 0.041 | 10.238 | < **0.001** | 0.342, 0.506 |
| Log$I_3$ | 0.081 | 0.021 | 3.939 | < **0.001** | 0.040, 0.122 |
| Log$L_{peceived}$ ~ log$I_1$ + log$I_3$ + (1 \| participant) + (1 \| participant: trial) | | | | | |
| (Constant) | 1.210 | 0.084 | 14.363 | < **0.001** | 1.043, 1.377 |
| Log$I_1$ | 0.127 | 0.016 | 7.718 | < **0.001** | 0.094, 0.159 |
| Log$I_3$ | − 0.014 | 0.008 | − 1.720 | 0.088 | − 0.030, 0.002 |

*The values for perceived heaviness for one participant were found to be outliers at the alpha level of 0.05 and thus excluded from all analyses

Boldface values indicate statistical significance

**Table 3** Outcomes of linear regressions (perceptual judgements against EMG activity)

| | Variable | $b$ | SE ($b$) | $\beta$ | $t$ | $P$ |
|---|---|---|---|---|---|---|
| Perceived heaviness, $H_{perceived}$ regressed against... | | | | | | |
| Biceps brachii | (Constant) | 6.437 | 37.521 | | 0.172 | 0.864 |
| | Normalized EMG | 36.225 | 6.286 | 0.505 | 5.763 | **< 0.001** |
| Flexor carpi radialis | (Constant) | 122.845 | 30.650 | | 4.008 | **< 0.001** |
| | Normalized EMG | 22.885 | 7.088 | 0.312 | 3.229 | **0.002** |
| Flexor carpi ulnaris | (Constant) | 55.242 | 55.586 | | 0.994 | 0.323 |
| | Normalized EMG | 38.524 | 13.032 | 0.287 | 2.956 | **0.004** |
| Perceived length, $L_{perceived}$ regressed against... | | | | | | |
| Biceps brachii | (Constant) | 63.914 | 3.636 | | 17.563 | **< 0.001** |
| | Normalized EMG | 1.555 | 0.610 | 0.240 | 2.549 | **0.012** |
| Flexor carpi radialis | (Constant) | 69.768 | 2.836 | | 24.603 | **< 0.001** |
| | Normalized EMG | 0.775 | 0.658 | 0.114 | 1.178 | 0.242 |
| Flexor carpi ulnaris | (Constant) | 70.161 | 5.100 | | 13.757 | **< 0.001** |
| | Normalized EMG | 0.667 | 1.197 | 0.054 | 0.557 | 0.579 |

Boldface values indicate statistical significance

## Results

An LME revealed that perceived heaviness, $H_{perceived}$, was a "single-valued function" of the eigenvalues $I_1$ and $I_3$: $H_{perceived}$ (no units) = 0.524 ($I_1^{0.423} \times I_3^{0.081}$) $r^2 = 0.825$ (Table 2). Here, single-valued function implies that a single specifying variable—the moment of inertia, $I$—specified perceived heaviness. Any given value of $I$ gave rise to a given perception, and as a corollary, a given perception was brought about by a given value of $I$. The positive exponents on $I_1$ and $I_3$ indicate that the more the wielded object resisted rotation about the longitudinal axis and an axis perpendicular to the longitudinal axis, the greater was the perceived heaviness (Fitzpatrick et al. 1994; Carello et al. 1998). We then used a linear regression to test if perceived heaviness obtained by this function, which we refer to as $H_{theoretical}$, predicted the perceived heaviness obtained experimentally, $H_{perceived}$, averaged across all participants: $H_{theoretical}$ significantly predicted $H_{perceived}$ ($\beta = 0.938$, $t_7 = 7.166$, $P < 0.001$) and also explained a significant proportion (88.0%) of the variance in $H_{perceived}$ (Fig. 3a).

Another LME revealed that perceived length, $L_{perceived}$, was also a single-valued function of $I_1$ and $I_3$: $L_{perceived}$ (cm) = 16.218 ($I_1^{0.127} \times I_3^{-0.014}$), $r^2 = 0.641$ (Table 2). Here, the positive exponent on $I_1$ indicates that the more the wielded object resisted rotation about the longitudinal axis, the greater was the perceived length; and the negative exponent on $I_3$ indicates that the object's resistance to rotation along an axis perpendicular to the longitudinal axis accounted for the mass being increasingly (and selectively) distributed laterally, resulting in reduction in the perceived length (Fitzpatrick et al. 1994; Carello et al. 1998). As in the

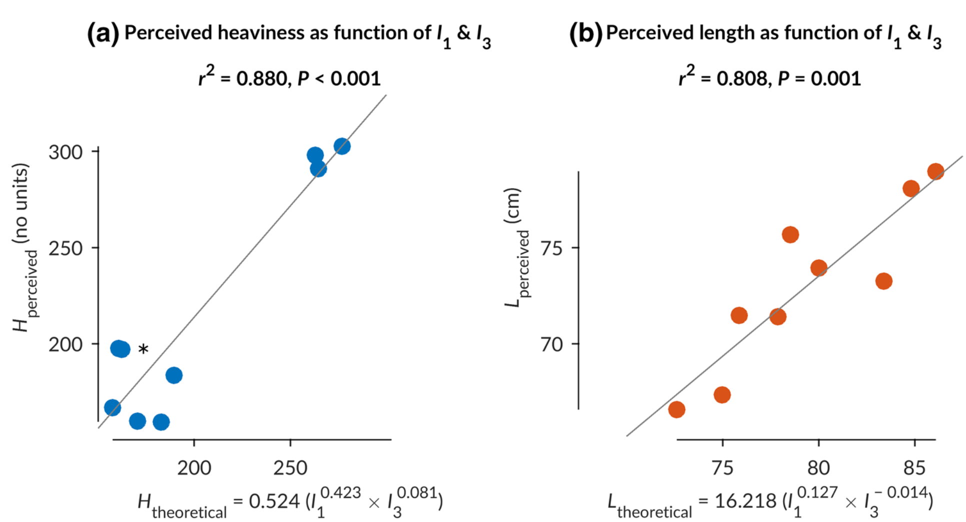



**Fig. 3** Relationships between perceptual judgments (of heaviness, $H_{perceived}$, and length, $L_{perceived}$) and the moment of inertia, $I$ ($n = 9$). **a** $H_{perceived}$ as function of $I_1$ and $I_3$. **b** $L_{perceived}$ as function of $I_1$ and $I_3$. *Two data points are coinciding

above analysis (i.e., with $H_{perceived}$), we used a linear regression to test if perceived length obtained by this function, which we refer to as $L_{theoretical}$, predicted the perceived length obtained experimentally, $L_{perceived}$, averaged across all participants: $L_{theoretical}$ significantly predicted $L_{perceived}$ ($\beta = 0.899$, $t_7 = 5.429$, $P = 0.001$) and also explained a significant proportion (80.8%) of the variance in $L_{perceived}$ (Fig. 3b).

Perceived heaviness and perceived length each could be expressed as a single-valued function of $I_1$ and $I_3$, although the exponents of $I_1$ and $I_3$ in the two functions were distinct ($I_1^{0.423}$ and $I_3^{0.081}$ for heaviness vs. $I_1^{0.127}$ and $I_3^{-0.014}$ for length). That is, $I$ specified both the heaviness and length of the wielded objects, but it did so differently. Thus, to investigate whether and how muscular effort mediated perception of heaviness and length differently, we examined the relationships between perceptual judgments of heaviness and length and the corresponding normalized EMG activity of biceps brachii, flexor carpi radialis, and flexor carpi ulnaris across all participant–object pairs.

Although we analyzed EMG signals for the entire 45 s during which the participants lifted and wielded the object, Fig. 4 illustrates sample EMG activity of biceps brachii, flexor carpi radialis, and flexor carpi ulnaris for one participant wielding Objects 3, 6, and 9 in a 2.5 s time window (25.0–27.5 s).

Individually regressing perceived heaviness, $H_{perceived}$ (no units) against normalized EMG activity (μV) of each muscle revealed that normalized EMG activity significantly predicted $H_{perceived}$: biceps brachii ($\beta = 0.505$, $t_{97} = 5.763$, $P < 0.001$), flexor carpi radialis ($\beta = 0.312$, $t_{97} = 3.229$, $P = 0.002$), and flexor carpi ulnaris ($\beta = 0.287$, $t_{97} = 2.956$, $P = 0.004$). (Full results are described in Table 3.) Normalized EMG activity also explained a significant (but relatively small) proportion of the variance in $H_{perceived}$: 25.5% for biceps brachii (Fig. 5a), 9.7% for flexor carpi radialis (Fig. 5b), and 8.3% for flexor carpi ulnaris (Fig. 5c).

Individually regressing perceived length, $L_{perceived}$ (cm) against (normalized) EMG activity (μV) of each muscle revealed that EMG activity significantly predicted $L_{perceived}$ for biceps brachii ($\beta = 0.240$, $t_{106} = 2.549$, $P = 0.012$), but not for the other two muscles: flexor carpi radialis ($\beta = 0.114$, $t_{106} = 1.178$, $P = 0.242$) and flexor carpi

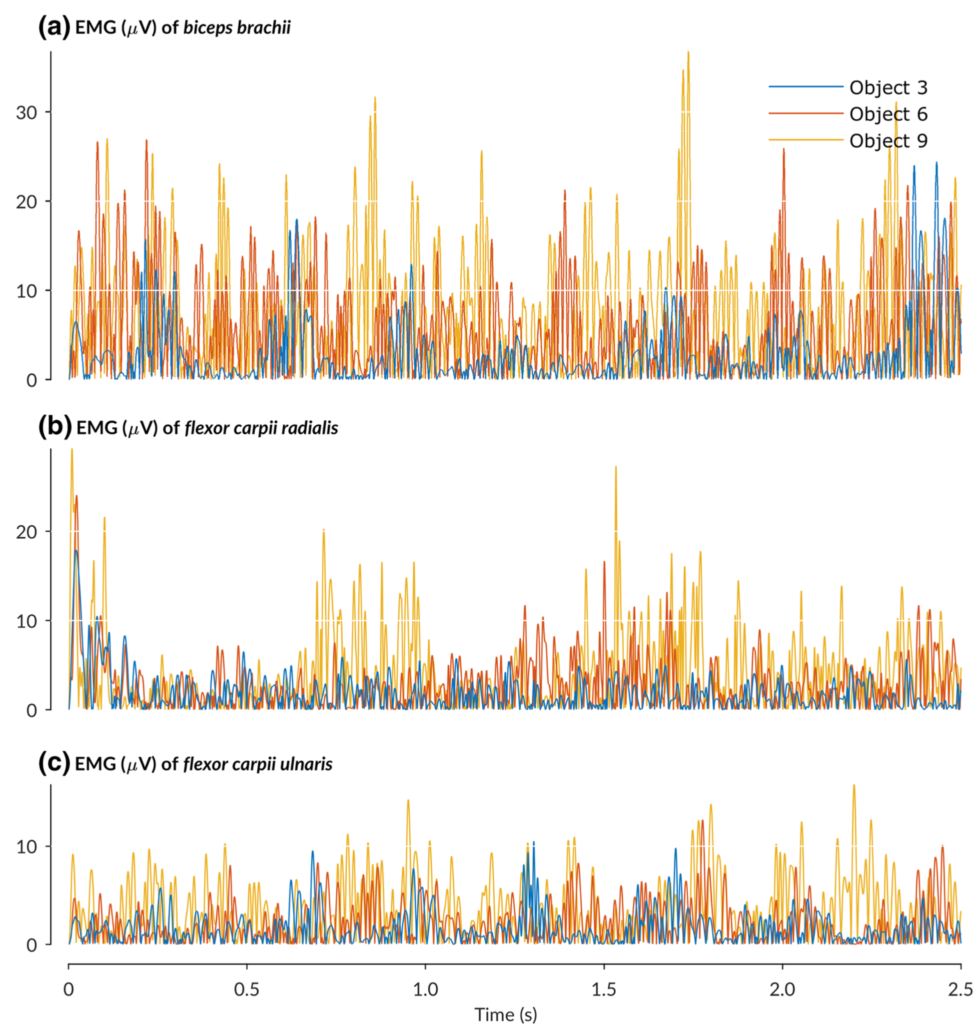



**Fig. 4** Sample EMG activity in the three muscles for one participant wielding objects 3, 6, and 9 in a 2.5 s time window (25.0–27.5 s). **a** Biceps brachii. **b** Flexor carpi radialis. **c** Flexor carpi ulnaris

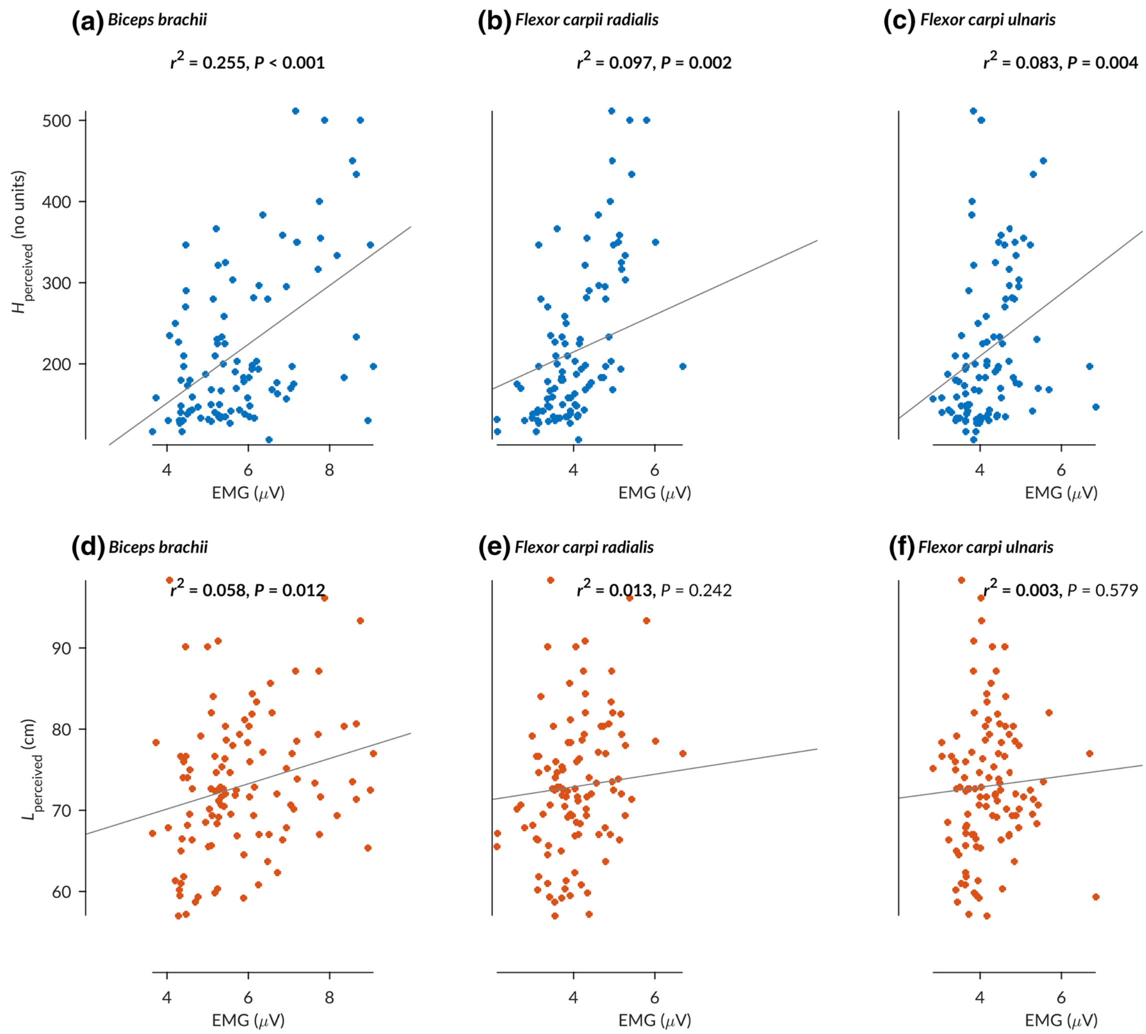



**Fig. 5** Perceptual judgments of heaviness, $H_{\text{perceived}}$, and length, $L_{\text{perceived}}$, regressed against [normalized] EMG activity across all participant–object pairs. **a–c** $H_{\text{perceived}}$ ($n=99$; 11 participants × 9 objects). **a** Biceps brachii. **b** Flexor carpi radialis. **c** Flexor carpi ulnaris. **d–f** $L_{\text{perceived}}$ ($n=108$; 12 participants × objects). **d** Biceps brachii. **e** Flexor carpi radialis. **f** Flexor carpi ulnaris

ulnaris ($\beta=0.054$, $t_{106}=0.557$, $P=0.579$). (Full results are described in Table 3.) While EMG activity explained a significant but tiny proportion of the variance (5.8%) in $L_{\text{perceived}}$ for biceps brachii (Fig. 5d), it did not explain any proportion of the variance in $L_{\text{perceived}}$ for the other two muscles: 1.3% for flexor carpi radialis (Fig. 5e) and 0.3% for flexor carpi ulnaris (Fig. 5f).

To summarize, the moment of inertia, $I$, provided the informational support for perception of both heaviness and length via dynamic touch. Perceived heaviness showed a direct and linear relationship with EMG activity for biceps brachii, flexor carpi radialis, and flexor carpi ulnaris. However, while perceived length showed a very weak relationship with EMG activity of biceps brachii, we found no association between perceived length and EMG activity of flexor carpi radialis and flexor carpi ulnaris.

## Discussion

Here, we investigated how muscular effort mediates perception of heaviness and length via dynamic touch. Twelve participants wielded nine occluded elongated objects of distinct moments of inertia and reported their perceptual judgments of heaviness and length. We measured EMG activity of the participants' biceps brachii, flexor carpi radialis, and flexor carpi ulnaris muscles during wielding. We found that distinct single-valued functions of the eigenvalues $I_1$ and $I_3$ of the inertial tensor, $I$, closely predicted both perceived heaviness and length of the wielded objects. Perceived heaviness showed a direct and linear relationship with EMG activity of biceps brachii, flexor carpi radialis, and flexor carpi ulnaris. However, while perceived length showed a very weak relationship with EMG activity of biceps brachii, we found no association between perceived length and EMG activity of flexor carpi radialis and flexor carpi ulnaris. Thus, while the same physical variable—i.e., the moment of inertia—provides the informational support for perception of heaviness and length, distinct psychophysiological processes underlie perception of heaviness and length via dynamic touch.

Biomechanical implications of heaviness and length for perception via dynamic touch are very distinct. Although people can accurately perceive the length of rods supported at the other end by touching them with minimal effort (Burton and Turvey 1990; Carello et al. 1992), they are unlikely to perceive the heaviness of such supported objects with minimal effort. At a minimum, the perceiver must exert a force proportional to the weight of an object (i.e., equivalent to its weight) while lifting or wielding (Waddell et al. 2016; Waddell and Amazeen 2017, 2018a, b). However, they might wield a lighter object by exerting greater (i.e., excessive) muscular effort and still perceive its heaviness with reasonable accuracy. Thus, while a particular amount of muscular effort is necessarily required to perceive heaviness, any amount of muscular effort above a minimum threshold can equally enable perception of length. Accordingly, in our study, perceived heaviness showed a direct, linear relationship with EMG activity, but there was no association between perceived length and EMG activity, indicating that muscular effort differentially mediates perception of heaviness and length. Likewise, perception of width, shape, and orientation of a wielded object is likely similar with length, in that perception requires any amount of muscular effort above a threshold. In contrast, perception of compliance, pliability, and other such properties is likely similar with heaviness, in that muscular effort contributes more directly to their perception.

The magnitudes of muscular effort were the same for both the judgments of heaviness and length, but the two judgments were specified by distinct single-valued functions of $I_1$ and $I_3$. This pattern indicates that an attunement to different features of the resulting afferent neural stimulation contributed independently to judgments of heaviness and length (cf. Wagman et al. 2001; Withagen and Michaels 2005; Arzamarski et al. 2010). In this respect, our study has a limitation, in that the participants always first reported perceived heaviness and then perceived length. This ordering of responses perhaps biased judgments of heaviness and length, but again, should not change the significance of our findings. In the future, randomizing (or counterbalancing) the order of perceptual responses across participants (or groups of participants) will be preferred.

Overall, our study identifies an intricate, perception-specific relationship among the specifying variable (the moment of inertia, $I$), the psychophysiological process (neuromuscular effort), and perceptual judgments (heaviness and length). Our first finding that $I_1$ and $I_3$ closely predicted both perceived heaviness and length is entirely consistent with several decades of research that has established beyond doubt that the moment of inertia provides the informational support for perception via dynamic touch [see reviews by Carello and Turvey (2000); Turvey and Carello (2011)]. Our study's novel contribution to research on perception via dynamic touch is in showing that muscular effort contributes directly to perception of heaviness, but likely only serves as a medium for perception of length.

We note that muscular effort is a secondary variable in dynamic touch in that it contains the information required for perceptual judgments in much the same way that light does in vision or sound does in audition (Gibson 1966). In optics, for example, visual judgments remain constant despite changes in the brightness of illumination (though changes in brightness are recognizable as well). Reading in dim light is challenging, but the recognition of words remains constant across (most) levels of the brightness. Certain specifying variables in the optic array in addition to brightness provide the informational support for recognition of these words (Gibson 1979). Similarly, as our findings indicate, muscular effort is required to detect the eigenvalues of $I$, but a given property is perceived as a function of those eigenvalues, not as the exact amount of muscular effort. Just as brighter light makes reading easier, a greater magnitude of muscular effort can make the moment of inertia more salient.

The neuroanatomical basis of dynamic touch is likely a multifractal tensegrity (MFT) system in which the skin, connective tissue net, muscles, tendons, bones, joints, and nerve fibers together comprise a delicately balanced, interconnected mechanical structure held together by the finely tuned interactions among elements under tension or compression (see Turvey and Fonseca 2014; Schleip et al. 2014). In this system, localized forces (e.g., at a particular anatomical site) bring a global realignment of compression and tension forces throughout the system and thus are registered globally (i.e., at the level of the system as a whole). Consequently, specific patterns of tissue deformation, and not the identity of the deformed tissues, underlie perception via dynamic touch. Accordingly, perception is not limited to the activity of any particular muscle, but all muscles are implicated in the distribution of forces throughout the body. No surprise that people can perceive the heaviness of an object with reasonable consistency by wielding it with both the hand and the leg (Waddell and Amazeen 2018a). They can also perceive the length of an object with reasonable consistency by wielding it about their wrist, elbow, or shoulder (Pagano et al. 1993), and by wielding it with their limbs, torso, or head (Hajnal et al. 2007a, b; Palatinus et al. 2011; Wagman and Hajnal 2014; Wagman et al. 2017).

Our findings, in the light of the haptic modality as an MFT system, raise specific impending questions regarding the link between the psychophysical and psychophysiological processes underlying perception via dynamic touch. What structural or mechanical, physiological, and neurophysiological characteristics of this MFT system provide for the threshold detection of the specifying variables; in what specific ways does muscular effort contribute to this process? What is the nature of correspondence between patterns of distribution of tension and compression forces in the MFT and the resulting patterns in the afferent neural stimulation that ultimately constitute perceptual judgments?

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## Compliance with ethical standards

**Conflict of interest** The authors declare that no competing interests exist.

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