RESEARCH ARTICLE

Fractal fluctuations in muscular activity contribute to judgments of length but not heaviness via dynamic touch

Madhur Mangalam[1] · James D. Conners[1] · Damian G. Kelty-Stephen[2] · Tarkeshwar Singh[3]

Abstract

The applied muscular effort to wield, hold, or balance an object shapes the medium by which action-relevant perceptual judgments (e.g., heaviness, length, width, and shape) are derived. Strikingly, the integrity of these judgments is retained over a range of exploratory conditions, a phenomenon known as perceptual invariance. For instance, judgments of length do not vary with the speed of rotation, despite the greater muscular effort required to wield objects at higher speeds. If not the amount of muscular effort alone, then what features of the neuromuscular activity implicated while wielding objects contribute to perception via dynamic touch? In the present study, we investigated how muscular activity mediates perception of heaviness and length of objects via dynamic touch. We measured EMG activity in biceps brachii and flexor carpi radialis as participants wielded objects of different moments of inertia. We found that variation in the amount of muscular effort (literally, root-mean-square values of EMG activity) predicted variations in judgments of heaviness but not length. In contrast, fluctuations in the activity of biceps brachii and flexor carpi radialis were fractal, and variation in the degree of fractality in the two muscles predicted variation in judgments of length. These findings reflect the distinct implications of dynamic touch for perception of heaviness and length. Perceptions of length can be derived from minimal effort, and muscular effort only shapes the medium from which judgments of length are derived. We discuss our findings in the context of the body as a multifractal tensegrity system, wherein perceptual judgments of length by wielding implicate, at least in part, rapidly diffusing mechanotransduction perturbations cascading across the whole body.

Keywords Biotensegrity · Effortful touch · Fractality · Haptic perception · Multifractality · Muscular effort · Perceptual invariance · Psychophysics

Introduction

Properties of an object such as length, size, and shape are typically relevant to using that object for reaching and/or acting upon a distant target (Bongers et al. 2003; van der Steen and Bongers 2011; Valk et al. 2016), and properties such as mass distribution are relevant to using an object for hammering, probing, or raking (Wagman and Carello 2001, 2003; Wagman and Taylor 2004; Michaels et al. 2007; Harrison et al. 2011). These properties are invariably tied to an object's moment of inertia and can be perceived by dynamically or effortfully touching these objects. This haptic [sub]modality—"dynamic touch"—supports the perceptions of such properties of a wielded object as heaviness, length, width, shape, and orientation in hand (Carello and Turvey 2000; Wagman and Carello 2001; Michaels et al. 2007; Turvey and Carello 2011; Mangalam et al. 2018b). The applied muscular effort to wield, hold, or balance an object shapes the medium by which action-relevant perceptual judgments are derived. Surprisingly, the integrity of these judgments is retained over a range of exploratory conditions, a phenomenon known as perceptual invariance. For instance, judgments of heaviness do not vary when objects are rotated at varying speed despite a greater amount of muscular effort being required

✉ Madhur Mangalam
  madhur.mangalam@uga.edu

✉ Tarkeshwar Singh
  t.singh@uga.edu

[1] Department of Psychology, University of Georgia, Athens, GA, USA

[2] Department of Psychology, Grinelle College, Grinelle, IA, USA

[3] Department of Kinesiology, University of Georgia, Athens, GA, USA

to rotate objects at higher speeds (Streit et al. 2007a, b). Similarly, wielding the same objects in air and water requires substantially different levels of muscular effort, but perception of length remains constant across the two media (Pagano and Donahue 1999; Pagano and Cabe 2003; Mangalam et al. 2017, 2018c). If not the amount of muscular effort alone, then what features of the neuromuscular activity implicated, while wielding objects contribute to perception via dynamic touch? Understanding the relationship between neuromuscular activity (wielding kinetics), exploratory movements (wielding kinematics), and perceptual judgments could explain perceptual constancy.

Perception via dynamic touch

Perception via dynamic touch involves the detection of three moments of inertia that together quantify how an object's mass is distributed in three-dimensional space. The joint torque, τ_{joint}, required to initiate the rotational motion of an object about a point of rotation in a joint depends on its moment of inertia, as modeled in the following equation:

$$\tau_{joint} = I\alpha - mgr \cdot \cos(\theta),$$

such that if the object is rotated about the wrist, m is the mass of the hand–object dyad, g is acceleration due to gravity, r is the radius of gyration about the wrist, and θ is the angle of the object relative to the horizontal. $I\alpha$ represents the dynamic torque, $\tau_{dynamic}$, due to the hand–object dyad's rotational motion, while $mgr \cdot \cos(\theta)$ represents the static torque, τ_{static}, due to the hand–object dyad's weight (the negative sign reflects that acceleration due to gravity is directed downwards). I is the moment of inertia and α is the angular acceleration. The wrist movements while wielding the object contribute to the detection of I.

I of a freely wielded object—or the degree to which it resists being rotated back and forth, up and down, or twisted—is represented by a 3×3 matrix; the "inertia tensor" of the hand–object dyad (Fig. 1). The eigenvalues I_1, I_2, and I_3 specify the resistance of that object to angular acceleration about its symmetry axes. Distinct combinations of the largest and the smallest eigenvalues, I_1 and I_3, specify the length and width of such objects (Fitzpatrick et al. 1994; Turvey et al. 1998). The ratio of I_1 and I_2 specifies the distribution of mass and thereby the shape of such objects (Burton et al. 1990). I_1, I_2, and I_3 together determine the influence of an object's physical dimensions on perception of its heaviness (Amazeen and Turvey 1996; Turvey et al. 1999; Shockley et al. 2004). How these combinations and their perceptual implications are reflected in behavior and activity of the biophysical substrate remains a question of serious interest.
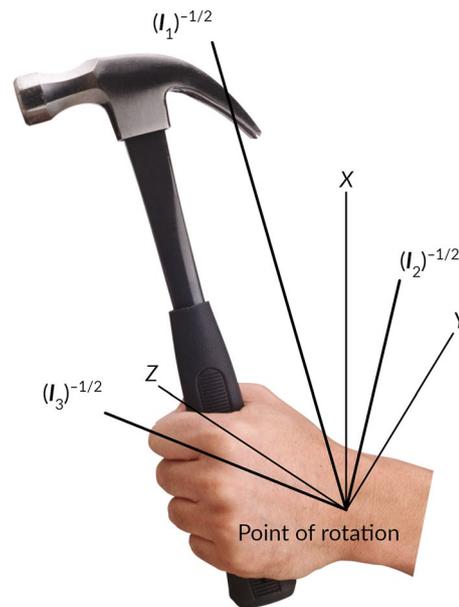
Component of I	Property of object
I_1 & I_3	Length & width
I_1, I_2, & I_3	Shape

Fig. 1 Eigenvalues, I_1, I_2, and I_3, of the inertial tensor of the hand–object dyad, I (the origin of the coordinate system lies at some point in the wrist). The combinations of eigenvalues and the properties which they specify are tabulated below

Tensegrity hypothesis: a bodywise tensegrity system provides the foundation for dynamic touch

The biophysical substrate of dynamic touch is hypothesized to be a multifractal tensegrity (MFT) system, wherein the shape and stability of the constituents of each scale—individual cell at the lowest scale to whole body at the highest scale—is derivative of continuous tension and discontinuous compression (Turvey and Fonseca 2014; Schleip et al. 2014). The skin, connective tissue net, muscles, tendons, bones, joints, and nerve fibers comprise a delicately balanced, interconnected mechanical structure held together by the finely tuned interactions among elements under tension or compression. Consequently, locally applied forces (e.g., at a particular anatomical site) result in the global realignment of forces and are thus registered globally. Such a global and distributive nature of the haptic perceptual system implies no limit to the number of realizable perceptual states, as distinct patterns of force distributions may give rise to identical perceptual judgment(s). Tensegrity architecture supports "mechanotransduction", the rapid propagation of local perturbations across the global architecture (Nelson et al. 2005; Ingber 2006,

2010). The local interactions among the components of a complex system such as an MFT shape global behavior, percolating over a range of scales in a temporally correlated manner (Goldberger et al. 1990, 2002; Ducharme and van Emmerik 2018). Consistent with this description of the haptic perceptual system of dynamic touch, people can perceive the length of an object with reasonable consistency by wielding it about their wrist, elbow, or shoulder (Pagano et al. 1993), as well as by wielding it with their limbs, torso, or head (Hajnal et al. 2007b, a; Palatinus et al. 2011; Wagman and Hajnal 2014; Wagman et al. 2017). These findings support situates fractal patterns in movements in the framework of the MFT hypothesis and highlights the abstractness of the [sub]modality of dynamic touch.

Fractal fluctuations in wielding kinematics and judgments of length via dynamic touch: preliminary support for the tensegrity hypothesis

Current interest in applying fractal geometry to topics in the study of living systems began with fractal applications to physiology (Goldberger et al. 1990, 2002; Peng et al. 1994, 1995; Sturmberg et al. 2015). Mounting evidence suggests that spatiotemporal variation in fractal fluctuations in movements supports perception via dynamic touch (Stephen et al. 2010; Stephen and Hajnal 2011; Palatinus et al. 2013; Kelty-Stephen and Dixon 2014). The identification of fractal fluctuations in the kinetics of exploratory movements would further facilitate an understanding of the modal abstractness of dynamic touch.

Measurable patterns in signal variability reflect a power-law relationship between fluctuation in the strength of the signal (literally, root mean square or RMS value) and timescale at which this variability is observed. This relationship exhibits scale invariance; that is, the rate of signal decay is identical for fluctuation over a range of timescales [for an in-depth discussion of power laws and scale invariance in perceptual judgments, see Luce (2002); Steingrimsson and Luce (2006, 2007)]. The degree of fractality in these cases is typically indexed by the strength of the power-law relationship between fluctuation and timescale (Mandelbrot 1982, 1999). The scaling exponent, H, describes the strength of this power-law relationship. As an indicator of temporal correlations, H is related to correlation coefficient C, such that

$$C(t) = 2^{2H-1} - 1.$$

Evidence that perceived length varies with fractal scaling in exploratory kinematics supports the hypothesis that fractality characterizes the organization of the haptic perceptual system of dynamic touch. Stephen et al. (2010) hypothesized that fractal fluctuations in exploratory kinematics of the hand grasping an experimental object would entail fluctuation at all time scales, allowing perceptual systems a flexible way to detect information at all time scales. The authors found that fluctuations in the kinematics of exploratory wielding movements were highly fractal and that a fractal-scaling exponent predicted individual variation in judgments of length. The authors hypothesized that their findings would extend to all timescales: shorter (i.e., attunement to the specifying variable, that is, the moment of inertia), intermediate (i.e., calibration of the specifying variable), and longer (i.e., learning and recalibrating after feedback). Later, Stephen and Hajnal (2011) found that fractal fluctuations in exploratory kinematics also support the transfer of calibration to anatomically different limbs (i.e., from hand to foot and foot to hand) and the degree of fractality predicts differences in the transfer of calibration. These latter findings by Stephen and Hajnal (2011) conceptually replicated the findings by Stephen et al. (2010) while further elaborating that qualitative differences in exploratory kinetics across different anatomical structures could be understood through the more generic, quantitative framework of changing fractal fluctuations.

Advancing the tensegrity hypothesis: fractal fluctuations in muscular activity and judgments of length via dynamic touch

Evidence supports the substantial role of fractality in the exploratory kinematics of wielding for perception of length via dynamic touch (Stephen et al. 2010; Palatinus et al. 2013), and this evidence coincides with the hypothesis that a bodywise MFT serves as a medium for perception via dynamic touch. Taking these understandings to their next logical step implicates fractality in the biophysical substrate of dynamic touch. Specifically, if a higher degree of fractality in muscular activity facilitates faster and more comprehensive diffusion of forces at all relevant scales of time and space, then we should be able to predict variation in perceptual judgments based on variation in the degree of fractality in muscular activity implicated in wielding.

In a study investigating the role of muscular activity of two hand muscles: biceps brachii and flexor carpi radialis, in perception of distinct properties of wielded objects via dynamic touch—specifically, heaviness and length (Mangalam et al. 2018a), we analyzed EMG recordings of activity in biceps brachii and flexor carpi radialis as participants wielded the objects of different moments of inertia and reported their judgments of heaviness and length. We found that judgments of heaviness varied in direct relation with the RMS of EMG activity in both biceps brachii and flexor carpi radialis. This finding confirmed the previously reported positive relationship between the amount of muscular effort and perceptual judgments of heaviness (Waddell et al. 2016; Waddell and Amazeen 2018a); judgments of heaviness do not vary whether an object is wielded about the hand or

the leg (Waddell and Amazeen 2018a). Notably, exploratory kinematics mediate this influence of muscular effort on judgments of heaviness—judgments of heaviness follow a function of the ratio of muscle activity to lifting acceleration (Waddell et al. 2016; Waddell and Amazeen 2018b). However, in our study, such role of muscular effort did not extend to perception of length, as we found no association between perceptual judgments of length and the RMS of muscular activity (Mangalam et al. 2018a). We, thus, concluded that some other [unknown] features of muscular activity besides the amount of muscular effort must provide for perception of properties such as length, width, and space.

In the present study, we reanalyzed EMG signals of biceps brachii and flexor carpi radialis recorded in our previous study (Mangalam et al. 2018a) to investigate the role of fractality in muscular activity in perception of heaviness and length via dynamic touch. Fractal fluctuations in the muscular activity would reflect fast and comprehensive, global diffusion of forces. Hence, local perturbations carried over muscular activity in the process of overcoming the moment of inertia of the wielded object result in rapidly diffusing mechanotransduction cascades across the whole MFT. Accordingly, we hypothesized that fluctuations in the activity of biceps brachii and flexor carpi radialis would be fractal, and that variation in the degree of fractality in the two muscles would predict variation in judgments of length. However, in the light of evidence that the amount of muscular effort decidedly contributes to perception of heaviness (Mangalam et al. 2018a), we anticipated that the degree of fractality in muscular activity would not predict the judgments of heaviness.

Materials and methods

Participants

Seven adult men and five adult women ($M \pm SD$ age = 22.0 ± 1.7 years, 19–31 years, 11 right-handed, 1 left-handed) voluntarily participated in the present experiment. 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) approved the present study.

Experimental objects

Each participant wielded nine experimental objects. Each object consisted of a dowel (oak, hollow or solid aluminum; diameter = 1.2 cm, length = 75.0 cm) weighted by stacked steel rings (4, 6, or 12 rings attached to the dowel at 20.0, 40.0, or 60.0 cm, respectively, from the grasping location; each ring's inner diameter = 1.4 cm, outer diameter = 3.4 cm, thickness = 0.2 cm; mass = 14 g). We enfolded a 15 cm long rubber grip of negligible mass and thickness around the base of each object to prevent a participant from cutaneously perceiving the composition of the dowel while wielding. Each object expressed a distinct moment of inertia, in terms of the combination of eigenvalues I_1 and I_3 (Table 1).

Experimental setup and procedure

We tested each participant in a 75–90-min session in which (s)he performed 27 trials: 9 objects × 3 trials/object. We randomized the order of presentation of the objects for each participant. The 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 heaviness of the wielded objects. We designated the mass of this object as 100 (no units) and instructed the participants 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, upon signaling 'lift' by the experimenter ($t = 0$ s), the participant grasped and lifted the experimental object. After

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
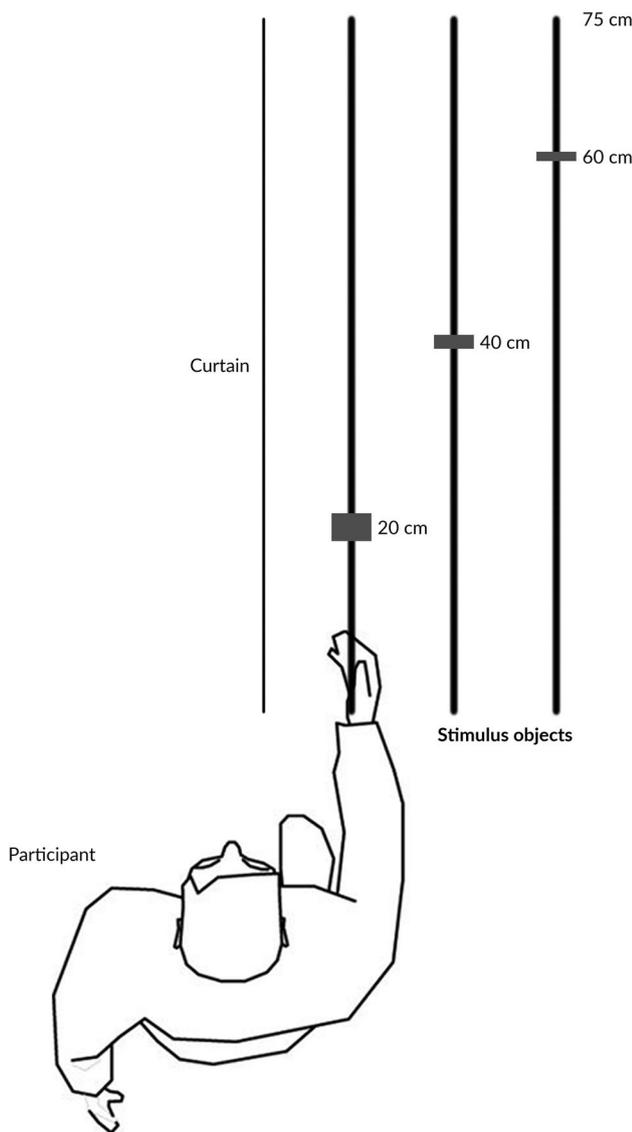
Fig. 2 Schematic illustration of the experimental objects and the experimental setup (top view; the participants could not see their right hand while wielding)

20 s ($t = 20$ s), upon signaling 'wield,' the participant wielded the object about his/her wrist. After 25 s ($t = 45$), upon signaling 'stop', the trial ended. The participant reported perceived heaviness of the wielded object (no units) relative to the reference object. The participant then reported the perceived length of the object by adjusting the position of a marker on a string-pulley assembly. The experimenter registered perceived length (in cm) on a 2-m-long scale attached to the base of the string-pulley assembly; the readings on the scale were not visible to the participant. We recorded EMG activities (in μV) in the participant's biceps brachii and flexor carpi radialis at 1926 Hz using a Delsys Trigno™ wireless EMG system (Delsys Inc., Boston, MA, USA). We chose biceps brachii as its activity has

been shown to contribute to perception of heaviness (Waddell et al. 2016; Waddell and Amazeen 2017, 2018b), and we chose flexor carpi radialis as it is implicated in the radial deviation of the wrist—a movement which is central to the wielding process. We attached the sensors parallel to the muscle fibers on the center of the muscle's belly. We rubbed the participant's skin with isopropyl alcohol pads before attaching the sensors to reduce skin impedance. We ensured the correct placement of the sensors by asking the participant to wield a demo object and monitoring the corresponding EMG activity on Delsys EMGworks software.

EMG signal processing

We computed the root-mean-square (RMS) values for each EMG signal for the entire 45.540 s window in biceps brachii and flexor carpi radialis. We processed each 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). We then fully rectified each EMG signal and computed its RMS value.

Detrended fluctuation analysis (DFA)

We used detrended fluctuation analysis (DFA) to compute the Hurst exponent, H, describing the strength of temporal correlations in EMG signals for biceps brachii and flexor carpi radialis. DFA was first developed to access the strength of temporal correlations in a given time series (Peng et al. 1994, 1995). The DFA proceeds by finding the first-order integration of a time series $x(t)$ with N samples to compute the cumulative sums of difference scores to produce the new time series:

$$y(t) = \sum_{i=1}^{N} x(t) - \overline{x(t)},$$

where $\overline{x(t)}$ is the grand mean of the time series. Next, a linear trend $y_n(t)$ is fit to nonoverlapping n-length bin of $y(t)$ and the root mean square (RMS; i.e., averaging the residuals) over each fit is computed. RMS over each bin size constitutes a fluctuation function $f(N)$:

$$f(N) = \sqrt{(1/N) \sum_{i=1}^{N} \left(x(t) - \overline{x(t)} \right)^2},$$

for $< N/4$. On standard scales, $f(N)$ is a power law:

$$f(N) \sim n^H,$$

where H is the scaling exponent. The closer H is to 1, the stronger are temporal correlations. H is estimated by logarithmically scaling the previous equation:

$$\log f(N) = H \log(n).$$

Hence, the slope of fluctuation functions in log–log plots represents H. It is important to note that temporal correlations can be present in both a time series and its first-order derivative. The original time series are often classified as fractional Brownian motions (fBm), wherein the first-order derivative of fBm is fractional Gaussian noise (fGn). Accordingly, the scaling exponents of a trajectory and its first-order derivative are denoted H_{fBm} and H_{fGn}, respectively.

To perform DFA over fluctuations in muscular activity, we first computed the [signed] first-order derivative for each of the [previously filtered] EMG signals for biceps brachii and flexor carpi radialis. We then obtained the DFA estimates of H_{fGn} for the unshuffled version and a shuffled version of [unsigned] first-order derivative for each [previously filtered] EMG signal for biceps brachii and flexor carpi radialis using the following bin sizes: 4, 8, 12,… 512.

Statistical analysis

We used linear mixed-effect (LME) models to examine variation in judgments of heaviness and length, as described in (Singer and Willett 2003), using the "nlme" package for *RStudio* (Pinheiro et al. 2018). Perceived heaviness, $H_{perceived}$, and perceived length $L_{perceived}$, each served as a dependent variable. The logarithms of the first and third moments of inertia ($\log I_1$ and $\log I_3$), EMG activity (in μV) for biceps brachii and flexor carpi radialis, and the DFA estimates of H_{fgn} encoding the strength of temporal correlations in EMG signals for biceps brachii and flexor carpi radialis served as the predictor variables. All predictors varied trial-by-trial within each combination of $\log I_1$ and $\log I_3$ specific to the current trial's experimental object. We describe each model in Tables 2, 3, 4. We also used paired-samples t tests to compare the values of H_{fGn} yielded by DFA performed on the unshuffled and a shuffled version of the first-order

Table 2 Results of linear mixed-effects models examining the contribution of I_1 and I_3 to judgments of heaviness, $H_{perceived}$, and length, $L_{perceived}$

	b	SE	$t_{284/310}$	p
$\log H_{perceived}{}^a \sim \log I_1 + \log I_3 + (1 \mid participant)$				
(Constant)	− 0.61	0.18	− 3.42	**< 0.001**
$\log I_1$	0.48	0.03	13.93	**< 0.001**
$\log I_3$	0.10	0.02	5.64	**< 0.001**
$\log L_{perceived} \sim \log I_1 + \log I_3 + (1 \mid participant)$				
(Constant)	− 1.20	0.08	− 2.64	**< 0.001**
$\log I_1$	0.13	0.02	7.80	**< 0.001**
$\log I_3$	− 0.01	0.01	− 1.38	0.079

Boldface values indicate statistical significance at $p < 0.05$

[a] 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

derivative of EMG signals for biceps brachii and flexor carpi radialis.

Results

Specifying variable supporting perception of length and heaviness via dynamic touch: the moment of inertia

Perceived heaviness, $H_{perceived}$, increased as the moment of inertia increased along the x-axis (i.e., I_1, $p < 0.001$) and along the longitudinal z-axis (I_3, $p < 0.001$) (Table 2). Perceived length, $L_{perceived}$, increased as the moment of inertia increased along the x-axis (I_1, $p < 0.001$), but did not vary with an increase in the moment of inertia along the longitudinal z-axis (I_3, $p = 0.079$) (Table 2) (Fig. 3).
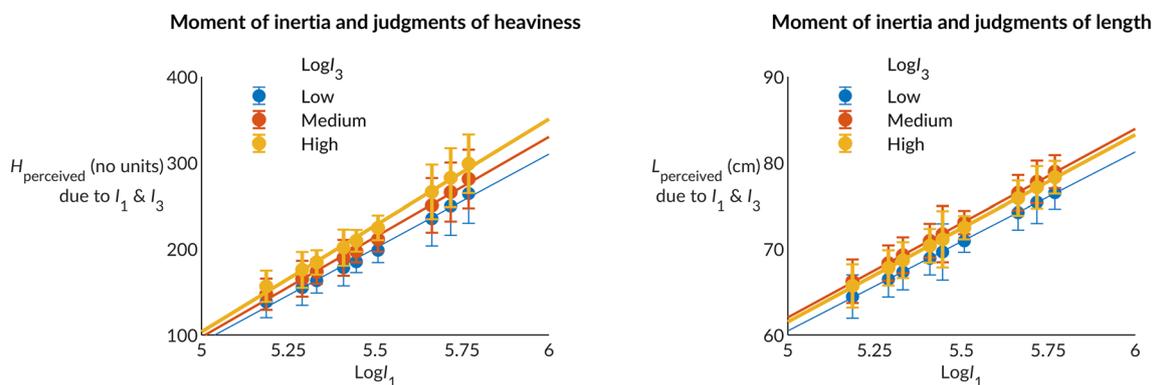

Fig. 3 The contribution of I_1 and I_3 to judgments of heaviness, $H_{perceived}$ (left panel), and length, $L_{perceived}$ (right panel). We defined "low", "medium", and "high" as the first quartile, median, and third quartile, respectively, of I_1 and I_3. Error bars indicate SE across all the trials

Table 3 Results of linear mixed-effects models examining the contribution of RMS of EMG to judgments of heaviness, $H_{perceived}$, above and beyond the contribution of I_1, and I_3

	b	SE	$t_{281/307}$	p
$H_{perceived} \sim (\log I_1 + \log I_3) + \text{EMG (biceps brachii)} \times \text{EMG (flexor carpi radialis)} + (1|\text{participant})$				
(Constant)	− 1118.86	98.75	− 11.33	**< 0.001**
$\log I_1$	198.47	19.35	10.26	**< 0.001**
$\log I_3$	47.32	8.76	5.40	**< 0.001**
EMG (biceps brachii)	12.02	2.95	4.08	**< 0.001**
EMG (flexor carpi radialis)	6.81	4.24	1.60	0.110
EMG (biceps brachii) × EMG (flexor carpi radialis)	− 0.22	0.33	− 0.66	0.508
$L_{perceived} \sim (\log I_1 + \log I_3) + \text{EMG (biceps brachii)} \times \text{EMG (flexor carpi radialis)} + (1|\text{Participant})$				
(Constant)	− 37.05	14.02	− 2.64	**0.009**
$\log I_1$	21.84	2.80	7.80	**< 0.001**
$\log I_3$	− 1.78	1.29	− 1.38	0.169
EMG (biceps brachii)	− 0.34	0.42	− 0.81	0.421
EMG (flexor carpi radialis)	− 0.89	0.60	− 1.47	0.143
EMG (biceps brachii) × EMG (flexor carpi radialis)	− 0.06	0.05	1.25	0.211

Boldface values indicate statistical significance at $p < 0.05$

Table 4 Results of linear mixed-effects models examining the effect of $\log I_1$ and $\log I_3$, and the degree of fractality in fluctuations in EMG activity, H_{fGn}, on judgments of heaviness, $H_{perceived}$, and length, $L_{perceived}$

	b	SE	$t_{281/307}$	p
$H_{perceived} \sim (\log I_1 + \log I_3) + H_{fGn} \text{ (biceps brachii)} \times H_{fGn} \text{ (flexor carpi radialis)} + (1|\text{Participant})$				
(Constant)	− 1471.83	535.37	− 2.75	**0.006**
$\log I_1$	257.69	19.34	13.32	**< 0.001**
$\log I_3$	58.70	9.32	6.30	**< 0.001**
H_{fGn} (biceps brachii)	14.18	523.96	0.03	0.978
H_{fGn} (flexor carpi radialis)	91.24	559.74	0.16	0.871
H_{fGn} (Biceps brachii) × H_{fGn} (flexor carpi radialis)	− 11.00	538.85	− 0.02	0.984
$L_{perceived} \sim (\log I_1 + \log I_3) + H_{fGn} \text{ (biceps brachii)} \times H_{fGn} \text{ (flexor carpi radialis)} + (1|\text{participant})$				
(Constant)	− 192.71	72.56	− 2.66	**0.008**
$\log I_1$	19.93	2.61	7.63	**< 0.001**
$\log I_3$	− 2.01	1.26	− 1.59	0.112
H_{fGn} (biceps brachii)	152.31	71.21	2.14	**0.033**
H_{fGn} (Flexor carpi radialis)	175.00	75.51	2.32	**0.021**
H_{fGn} (biceps brachii) × H_{fGn} (flexor carpi radialis)	− 163.66	72.65	− 2.25	**0.025**

Boldface values indicate statistical significance at $p < 0.05$

Amount of muscular activity supports perception of heaviness but not length

Above and beyond the known contributions of I_1 and I_3, RMS of EMG activity in biceps brachii significantly improved the predictions for judgments of heaviness (Table 3; left panel in Fig. 4). Specifically, $H_{perceived}$ increased with RMS of EMG activity in biceps brachii ($p < 0.001$). RMS of EMG activity in flexor carpi radialis did not improve predictions for the judgments of heaviness ($p = 0.110$). Figure 5 (left panels) provides a comparison of judgments of heaviness by trial with predictions from the model for two representative participants.

Regarding judgments of length, above and beyond the known contributions of I_1 and I_3, RMS of EMG activity in

neither biceps brachii nor in flexor carpi radialis improved the predictions for judgments of length: biceps brachii ($p = 0.421$), flexor carpi radialis ($p = 0.143$) (Table 4; right panel in Fig. 4). Figure 5 (right panels) provides a comparison of judgments of length by trial with predictions from the model for two representative participants.

Fractal fluctuations in muscular activity support perception of length but not heaviness

We computed the first-order derivative of each [previously filtered] EMG signal (Fig. 6 shows time series for a representative EMG signal in a 2.5 s window and its first-order derivative).
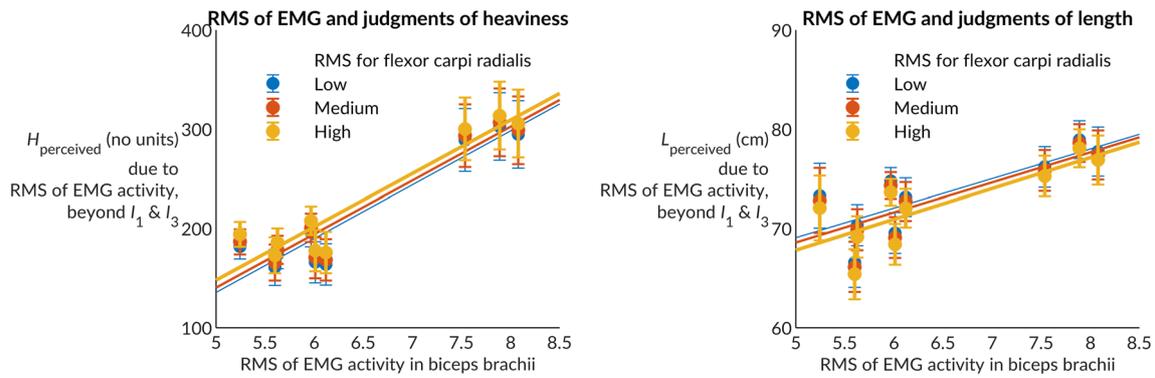
Fig. 4 The contribution of RMS of EMG to judgments of heaviness, $H_{\text{perceived}}$, and length, $L_{\text{perceived}}$, above and beyond the contribution of I_1, and I_3. We defined "low", "medium", and "high" as the first quar-tile, median, and third quartile, respectively, of a variable. Error bars indicate SE across all trials
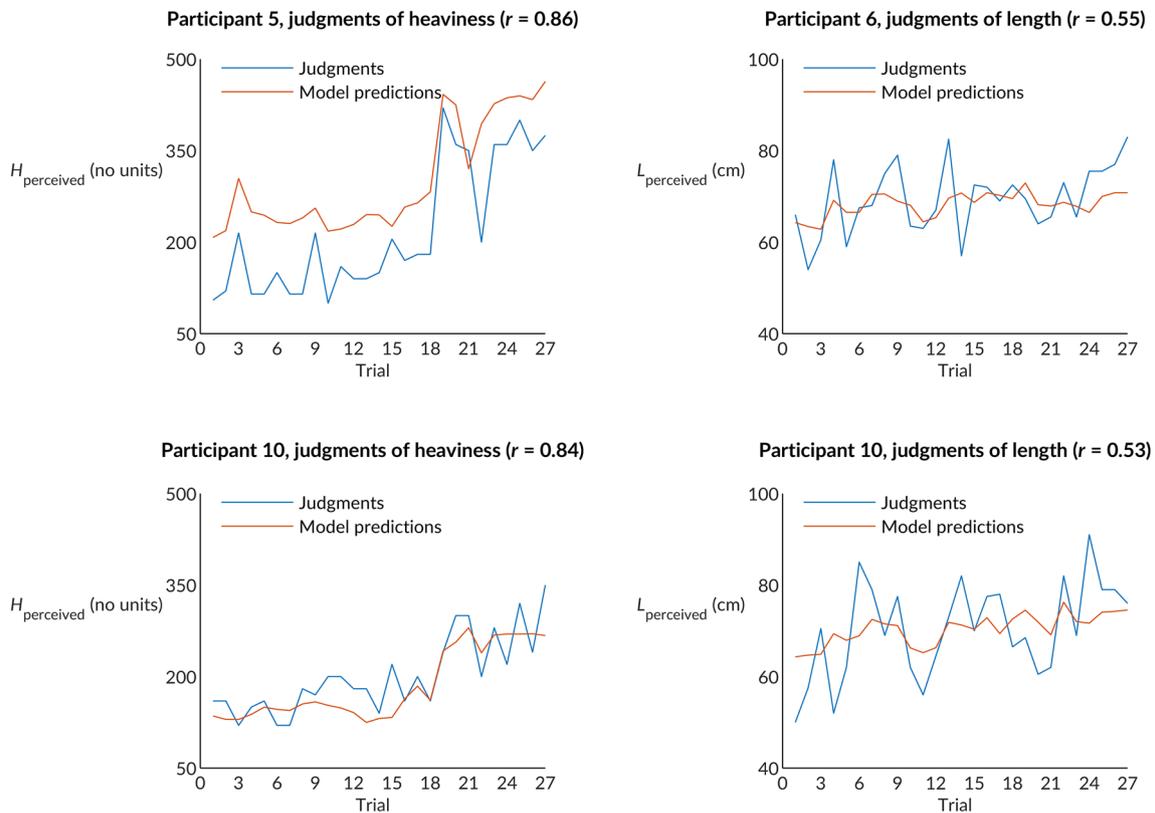

Fig. 5 Comparison of judgments of heaviness, $H_{\text{perceived}}$, and length, $L_{\text{perceived}}$, by trial with predictions from the model for two representative participants. The model consists of I_1 and I_3, and RMS of EMG of biceps brachii and flexor carpi radialis

To test for the presence of fractal fluctuations in EMG activity, we obtained DFA estimates of H_{fGn} for each of the unshuffled time series ($N = 324$, 12 participants $\times$ 9 objects/participant $\times$ 3 trials/object) of the first-order derivative of EMG signals for biceps brachii and flexor carpi radialis, along with a shuffled version for each time series. Shuffling destroys temporal correlations in a given

signal. Figure 7 depicts log–log plots of fluctuation function, $f(N)$, vs. bin size reflecting H_{fGn} yielded by DFA on the time series of the first-order derivative of EMG signals for a trial. The values were significantly higher than the values of H_{fGn} for the shuffled versions of the time series for biceps brachii ($M \pm \text{SE} = 1.00 \pm 0.09$ vs. 0.51 ± 0.01, paired-samples t test: $t_{323} = 16.78$, $p < 0.001$) and flexor

Time series for a representative EMG signal

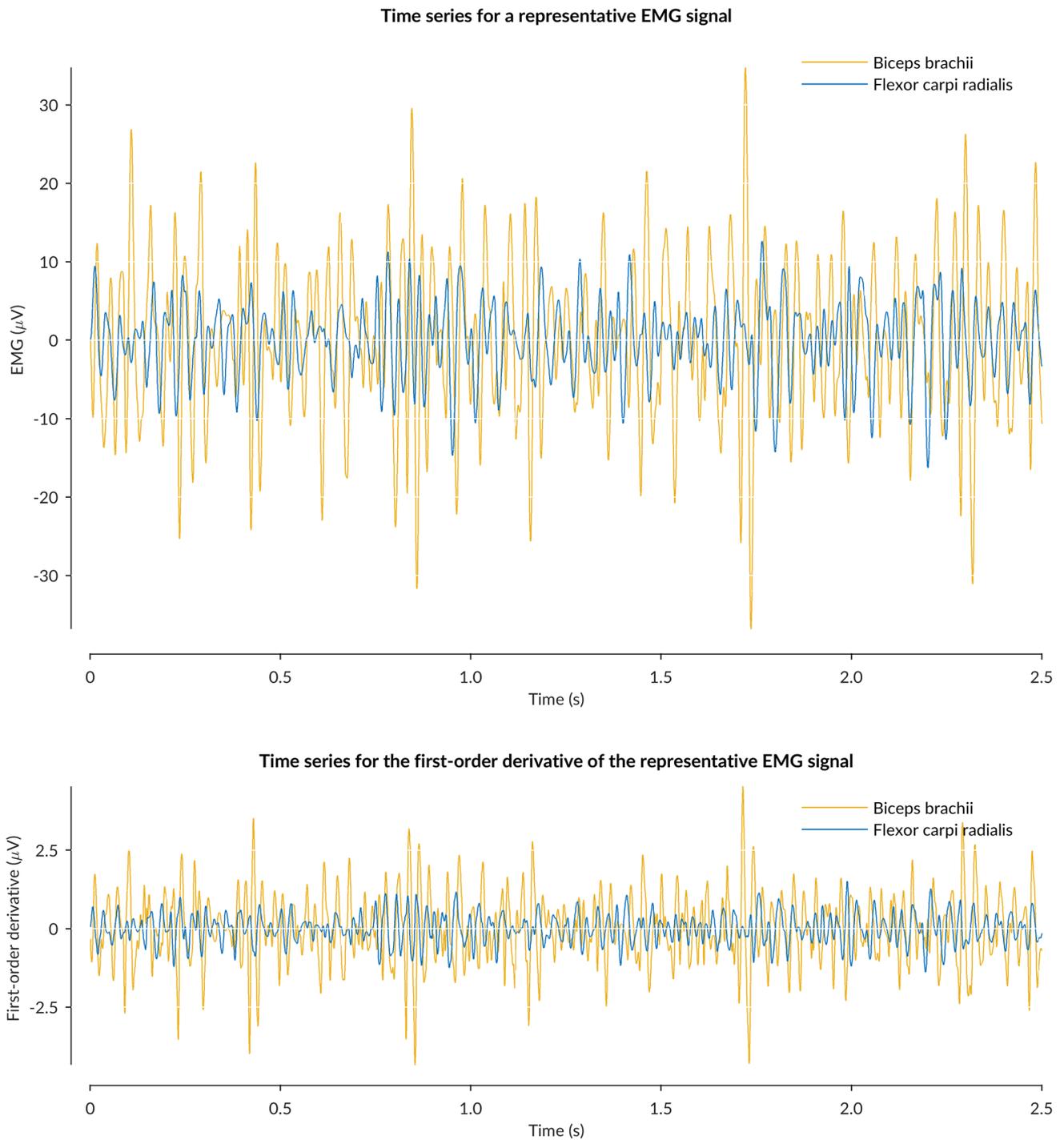## Time series for the first-order derivative of the representative EMG signal

Fig. 6 Time series for a representative EMG signal in a 2.5 s window (top panel) and its first-order derivative (bottom panel)

carpi radialis (1.01 ± 0.09 vs. 0.51 ± 0.01, $t_{323} = 16.79$, $p < 0.001$).

Above and beyond the known contributions of I_1 and I_3, the strength of fractal fluctuations in EMG activity in neither biceps brachii nor flexor carpi radialis improved the predictions for judgments of heaviness: biceps brachii ($p = 0.978$)

and flexor carpi radialis ($p = 0.871$) (Table 4; left panel in Fig. 8). Figure 9 (left panels) provides a comparison of judgments of heaviness by trial with predictions from the model for two representative participants.

Fig. 7 Log–log plots of the fluctuation function, $f(N)$, vs. bin size reflecting H_{fGn} yielded by the DFA performed on the time series for the first-order derivatives of EMG signals for biceps brachii (left panel) and flexor carpi radialis (right panel) for a representative trial
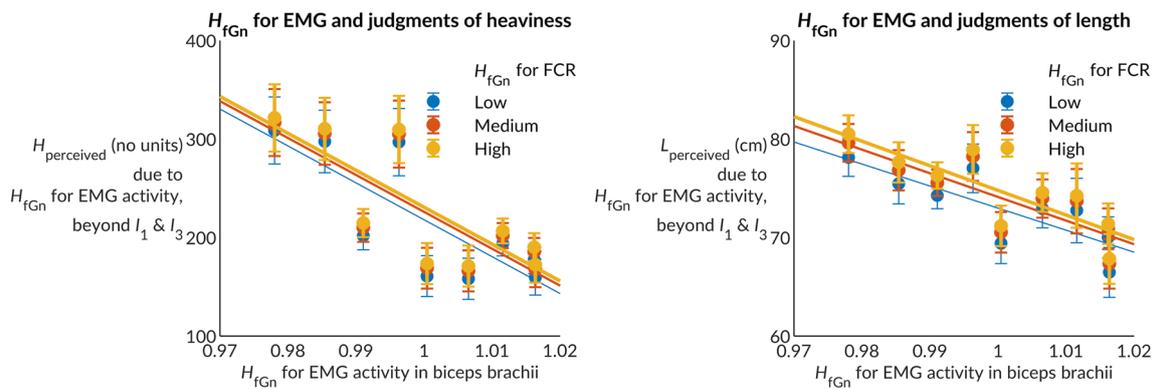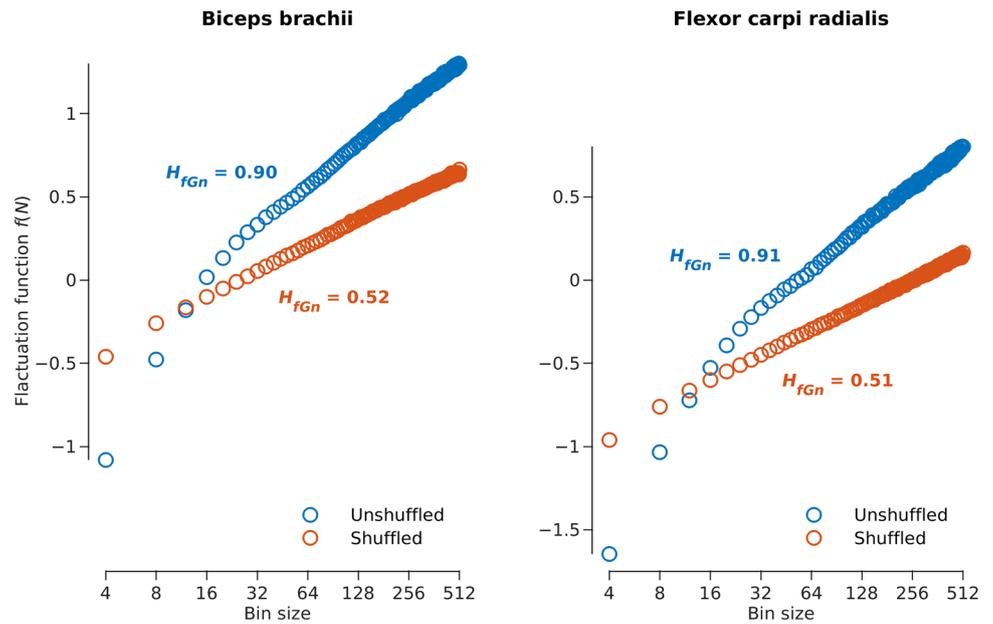

Fig. 8 The contribution of the degree of fractality in fluctuations in EMG activity, H_{fGn}, to judgments of heaviness, $H_{perceived}$, and length, $L_{perceived}$, above and beyond the contribution of I_1 and I_3. We defined "low", "medium", and "high" as the first quartile, median, and third quartile, respectively, of a variable. *FCR* Flexor carpi radialis. Error bars indicate SE across all trials

Regarding judgments of length, above and beyond the known contributions of I_1 and I_3, the degree of fractal fluctuations in EMG activity in both muscles biceps brachii and flexor carpi radialis significantly improved the predictions for judgments of length (Table 4; right panel in Fig. 8). Figure 9 (right panels) provides a comparison of judgments of length by trial with predictions from the model for two representative participants. Specifically, $L_{perceived}$ increased with H_{fGn} for EMG activity in biceps brachii ($p = 0.033$) and flexor carpi radialis ($p = 0.021$). In addition, a significant interaction between H_{fGn} for EMG activity in biceps brachii and flexor carpi radialis indicated that perceived length decreased as the degree of fractal

fluctuations in EMG activity in both muscles reduced simultaneously ($p = 0.025$).

Discussion

We investigated the role of fractality in muscular activity in perception of heaviness and length via dynamic touch. Our reanalysis of EMG signals from biceps brachii and flexor carpi radialis measured in our previous study (Mangalam et al. 2018a) revealed that fractality in muscular activity is associated with perception of length via dynamic touch. Consistent with our two hypotheses, fluctuations in EMG activity of biceps brachii and flexor carpi radialis were
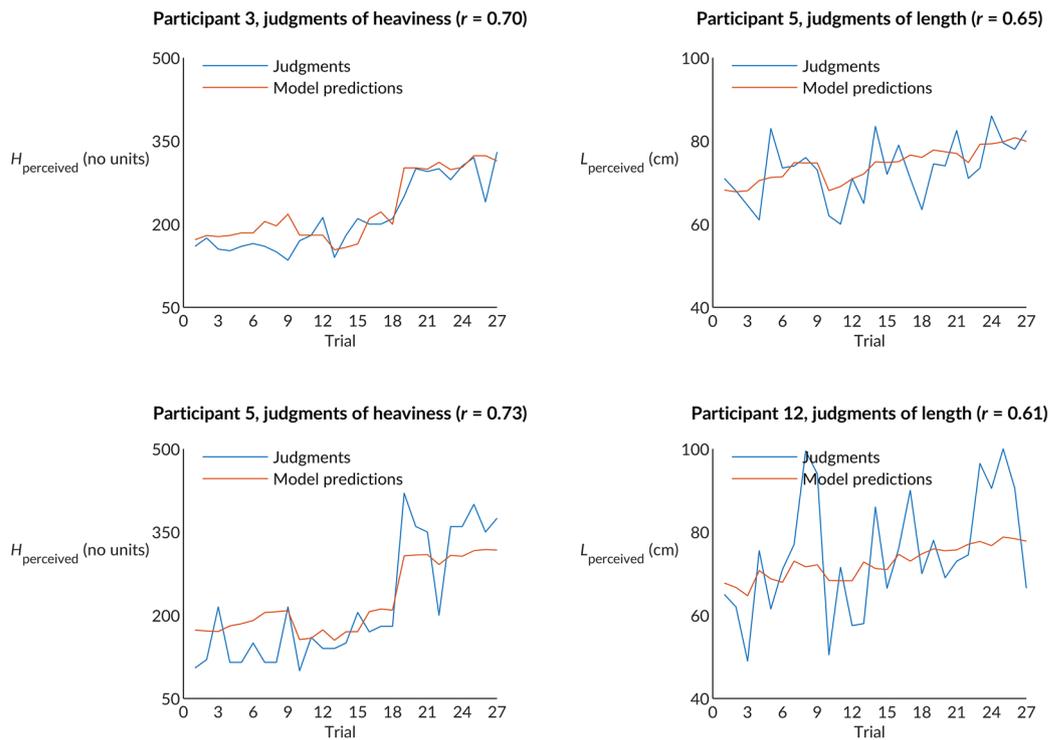
Fig. 9 Comparison of judgments of heaviness, $H_{perceived}$, and length, $L_{perceived}$, by trial with predictions from the model for two representative participants. The model consists of I_1 and I_3, and H_{fGn} of EMG of biceps brachii and flexor carpi radialis

fractal, that is, $H \sim 1$, and variation in the degree of fractality in the two muscles predicted judgments of length, but not heaviness. Judgments of heaviness, in contrast, were predicted by the amount of muscular effort—as measured by RMS of EMG activity (Mangalam et al. 2018a). Our most significant finding is that the strengths of fractalities for biceps brachii and flexor carpi radialis contributed synergistically to perceptions of length; that is, in a coupled but non-additive fashion. We discuss the first findings as evidence that muscular activity differentially mediates perception of heaviness and length via dynamic touch; and the second finding as evidence that dynamic touch reflects action and perception at the level of synergies.

Muscular activity differentially mediates perception of heaviness and length via dynamic touch

Our first finding that muscular effort differentially mediates the perception of heaviness and length reflects the distinct implications of dynamic touch for perception of heaviness and length [see (Mangalam et al. 2018a) for a discussion]. While people can perceive the lengths of rods supported at the other end fairly accurately by touching them with minimal effort (Burton and Turvey 1990; Carello et al. 1992a), they cannot do the same for perceptions of heaviness; at the minimum, wielders must lift an object with force greater

or equivalent to its weight to form these perceptual judgments (Waddell et al. 2016; Waddell and Amazeen 2017, 2018b, a). The present findings show that fractal fluctuations in muscular activity contribute to perception of length, regardless of the amount of muscular activity. It remains an open question to what degree perceptions of length, width, shape, and other affordance-relevant properties of objects share the same fractal basis (Carello et al. 1992b; Wagman and Hajnal 2014). Given that distinct combinations of I_1, I_2, and I_3 specify each of these dimensional properties in perceptual judgments (Burton et al. 1990; Fitzpatrick et al. 1994; Turvey et al. 1998), the fractal fluctuations in the muscular activity relevant to these perceptual judgments during wielding (and the muscles in which they emerge) may vary in specific, measurable ways.

Dynamic touch: action and perception at the level of synergies

Our findings demonstrate that perception via dynamic touch does not merely depend on the most superficial features of movement, but may have deeper roots in the fractal geometry of physiology. The finding that fractal fluctuations in the muscular activity of biceps brachii and flexor carpi radialis are together implicated in perception of length reflects the synergistic basis of action and perception in dynamic touch.

Specifically, the perceptual content for dynamic touch lies at the level of temporal correlation in muscular activity that is implicated in wielding specific objects (i.e., objects of different properties), as has been noted previously (Stephen et al. 2010; Stephen and Hajnal 2011; Palatinus et al. 2013; Kelty-Stephen and Dixon 2014). Accordingly, our fractal results suggest that patterns of neural activation for perceptual judgments may be highly interdependent across the stages of activation of the muscles implicated during wielding. We refer interested readers to a more extensive review on this topic: "action and perception at the level of synergies" (Turvey 2007). High fractality in biceps brachii activity was relevant to perception of length when and only when similarly high fractality in the patterns of neural activity was expressed in the activity of the flexor carpi radialis. These results suggest an important coupling in the function and activation of these two muscles with respect to perceptions of length via dynamic touch.

Our findings are a continuation of the ecological approach that recognizes the interdependence of perceptual judgments from the components and the flexibility with which smart perceptual systems can spontaneously assemble using different anatomical components (Gibson 1966, 1979). The ecological approach to the organization of behavior views dynamic touch in the light of a dynamically situated neural substrate residing over a bodywide multifractal tensegrity (MFT) system (Turvey and Fonseca 2014; Schleip et al. 2014). Rather than attributing action and perception solely to neural dynamics, this approach seeks to identify the patterns of coordination in the functioning of the tensegrity structures in specific behaviors that give rise to movement and the perceptual content with which it is coupled—that is, contributions of the MFT system to neural dynamics including but not limited to the contributions of initial mechanotransduction cascades (Hajnal et al. 2018). Patterns of correlated variability in physiological signals may reflect an ongoing influence of the MFT system in a measurable way.

Cross-scale interactivity allows effective coupling of the organism-environment dynamics to ecologically relevant perceptual states responsive to the changing affordances of the environment (Van Orden et al. 2003, 2005; Wallot and Kelty-Stephen 2018). Accordingly, fractal fluctuations in physiological signals find expression across all levels in systems that show strong coupling with the environment. The haptic [sub]modality of dynamic touch is one such system in which the role of fractal fluctuations extends fully throughout the perceptual process. Specifically, fractal fluctuations mediate the actor's physical interactions with an environmentally sourced object through coupling with the [sub]modality of dynamic touch. How movements constitute meaning can only be understood in the context of a dyadically coupled animal–environment system characterized by nonlinear interactions across scales that weave together the animal and his environment. Tensegrity architecture in morphology is ubiquitous in natural forms; an understanding of the co-creation of structure and function in these systems may lead to more profound insights regarding animal–environment enmeshment.

Compliance with ethical standards

References

Amazeen EL, Turvey MT (1996) Weight perception and the haptic size–weight illusion are functions of the inertia tensor. J Exp Psychol Hum Percept Perform 22:213–232

Bongers RM, Smitsman AW, Michaels CF (2003) Geometries and dynamics of a rod determine how it is used for reaching. J Mot Behav 35:4–22. https://doi.org/10.1080/00222890309602117

Burton G, Turvey MT (1990) Perceiving the lengths of rods that are held but not wielded. Ecol Psychol 2:295–324. https://doi.org/10.1207/s15326969eco0204_1

Burton G, Turvey MT, Solomon HY (1990) Can shape be perceived by dynamic touch? Percept Psychophys 48:477–487. https://doi.org/10.3758/BF03211592

Carello C, Turvey MT (2000) Rotational invariance and dynamic touch. In: Heller MA (ed) Touch, representation and blindness. Oxford University Press, New York, pp 27–66

Carello C, Fitzpatrick P, Domaniewicz I et al (1992a) Effortful touch with minimal movement. J Exp Psychol Hum Percept Perform 18:290–302. https://doi.org/10.1037/0096-1523.18.1.290

Carello C, Fitzpatrick P, Turvey MT (1992b) Haptic probing: perceiving the length of a probe and the distance of a surface probed. Percept Psychophys 51:580–598. https://doi.org/10.3758/BF03211655

Ducharme SW, van Emmerik REA (2018) Fractal dynamics, variability, and coordination in human locomotion. Kinesiol Rev 7:26–35. https://doi.org/10.1123/kr.2017-0054

Fitzpatrick P, Carello C, Turvey MT (1994) Eigenvalues of the inertia tensor and exteroception by the "muscular sense. Neuroscience 60:551–568. https://doi.org/10.1016/0306-4522(94)90264-X

Gibson JJ (1966) The senses considered as perceptual systems. Houghton Mifflin, Boston

Gibson JJ (1979) The ecological approach to visual perception. Houghton Mifflin, Boston

Goldberger AL, Rigney DR, West BJ (1990) Chaos and fractals in human physiology. Sci Am 262:42–49

Goldberger AL, Amaral LAN, Hausdorff JM et al (2002) Fractal dynamics in physiology: alterations with disease and aging. Proc Natl Acad Sci 99:2466–2472. https://doi.org/10.1073/pnas.012579499

Hajnal A, Fonseca S, Harrison S et al (2007a) Comparison of dynamic (effortful) touch by hand and foot. J Mot Behav 39:82–88. https://doi.org/10.3200/JMBR.39.2.82-88

Hajnal A, Fonseca S, Kinsella-Shaw JM et al (2007b) Haptic selective attention by foot and by hand. Neurosci Lett 419:5–9. https://doi.org/10.1016/j.neulet.2007.03.042

Hajnal A, Clark JD, Doyon JK, Kelty-Stephen DG (2018) Fractality of body movements predicts perception of affordances: evidence from stand-on-ability judgments about slopes. J Exp Psychol Hum Percept Perform 44:836–841. https://doi.org/10.1037/xhp0000510

Harrison SJ, Hajnal A, Lopresti-Goodman S et al (2011) Perceiving action-relevant properties of tools through dynamic touch: effects of mass distribution, exploration style, and intention. J Exp Psychol Hum Percept Perform 37:193–206. https://doi.org/10.1037/a0020407

Ingber DE (2006) Cellular mechanotransduction: putting all the pieces together again. FASEB J 20:811–827. https://doi.org/10.1096/fj.05-5424rev

Ingber DE (2010) From cellular mechanotransduction to biologically inspired engineering. Ann Biomed Eng 38:1148–1161. https://doi.org/10.1007/s10439-010-9946-0

Kelty-Stephen DG, Dixon JA (2014) Interwoven fluctuations during intermodal perception: fractality in head sway supports the use of visual feedback in haptic perceptual judgments by manual wielding. J Exp Psychol Hum Percept Perform 40:2289–2309

Luce RD (2002) A psychophysical theory of intensity proportions, joint presentations, and matches. Psychol Rev 109:520–532. https://doi.org/10.1037/0033-295X.109.3.520

Mandelbrot BB (1982) The fractal geometry of nature. W H Freeman, New York

Mandelbrot BB (1999) Multifractals and 1/f noise. Springer, New York

Mangalam M, Barton SA, Wagman JB et al (2017) Perception of the length of an object through dynamic touch is invariant across changes in the medium. Atten Percept Psychophys 79:2499–2509. https://doi.org/10.3758/s13414-017-1403-9

Mangalam M, Conners JD, Singh T (2018a) Muscular effort differentially mediates perception of heaviness and length via dynamic touch. Exp Brain Res. https://doi.org/10.1007/s00221-018-5421-1

Mangalam M, Pacheco MM, Fragaszy DM, Newell KM (2018b) Perceptual learning of tooling affordances of a jointed object via dynamic touch. Ecol Psychol 30:1–29. https://doi.org/10.1080/10407413.2018.1473714

Mangalam M, Wagman JB, Newell KM (2018c) Temperature influences perception of the length of a wielded object via effortful touch. Exp Brain Res 236:505–516. https://doi.org/10.1007/s00221-017-5148-4

Michaels CF, Weier Z, Harrison SJ (2007) Using vision and dynamic touch to perceive the affordances of tools. Perception 36:750–772. https://doi.org/10.1068/p5593

Nelson CM, Jean RP, Tan JL et al (2005) Emergent patterns of growth controlled by multicellular form and mechanics. Proc Natl Acad Sci USA 102:11594 LP–L11599

Pagano CC, Cabe PA (2003) Constancy in dynamic touch: length perceived by dynamic touch is invariant over changes in media. Ecol Psychol 15:1–17. https://doi.org/10.1207/S15326969ECO1501_01

Pagano CC, Donahue KG (1999) Perceiving the lengths of rods wielded in different media. Percept Psychophys 61:1336–1344. https://doi.org/10.3758/BF03206184

Pagano CC, Fitzpatrick P, Turvey MT (1993) Tensorial basis to the constancy of perceived object extent over variations of dynamic touch. Percept Psychophys 54:43–54. https://doi.org/10.3758/BF03206936

Palatinus Z, Carello C, Turvey MT (2011) Principles of part-whole selective perception by dynamic touch extend to the torso. J Mot Behav 43:87–93. https://doi.org/10.1080/00222895.2010.538767

Palatinus Z, Dixon JA, Kelty-Stephen DG (2013) Fractal fluctuations in quiet standing predict the use of mechanical information for haptic perception. Ann Biomed Eng 41:1625–1634. https://doi.org/10.1007/s10439-012-0706-1

Peng C-K, Buldyrev SV, Havlin S et al (1994) Mosaic organization of DNA nucleotides. Phys Rev E 49:1685–1689. https://doi.org/10.1103/PhysRevE.49.1685

Peng C-K, Havlin S, Stanley HE, Goldberger AL (1995) Quantification of scaling exponents and crossover phenomena in nonstationary heartbeat time series. Chaos An Interdiscip J Nonlinear Sci 5:82–87. https://doi.org/10.1063/1.166141

Pinheiro J, Bates D, DebRoy S, Sarkar D, Team RC (2018) nlme: Linear and nonlinear mixed effects models. R package version 3, pp 1–137. Retrieved from https://cran.r-project.org/package=nlme

Schleip R, Mechsner F, Zorn A, Klingler W (2014) The bodywide fascial network as a sensory organ for haptic perception. J Mot Behav 46:191–193. https://doi.org/10.1080/00222895.2014.880306

Shockley K, Carello C, Turvey MT (2004) Metamers in the haptic perception of heaviness and moveableness. Percept Psychophys 66:731–742. https://doi.org/10.3758/BF03194968

Singer JD, Willett JB (2003) Applied longitudinal analysis: modeling change and event occurrence. Oxford University Press, New York

Steingrimsson R, Luce RD (2006) Empirical evaluation of a model of global psychophysical judgments: III. A form for the psychophysical function and intensity filtering. J Math Psychol 50:15–29. https://doi.org/10.1016/j.jmp.2005.11.005

Steingrimsson R, Luce RD (2007) Empirical evaluation of a model of global psychophysical judgments: IV. Forms for the weighting function. J Math Psychol 51:29–44. https://doi.org/10.1016/j.jmp.2006.08.001

Stephen DG, Hajnal A (2011) Transfer of calibration between hand and foot: functional equivalence and fractal fluctuations. Atten Percept Psychophys 73:1302–1328. https://doi.org/10.3758/s13414-011-0142-6

Stephen DG, Arzamarski R, Michaels CF (2010) The role of fractality in perceptual learning: exploration in dynamic touch. J Exp Psychol Hum Percept Perform 36:1161–1173. https://doi.org/10.1037/a0019219

Streit M, Shockley K, Riley MA (2007a) Rotational inertia and multimodal heaviness perception. Psychon Bull Rev 14:1001–1006. https://doi.org/10.3758/BF03194135

Streit M, Shockley K, Riley MA, Morris AW (2007b) Rotational kinematics influence multimodal perception of heaviness. Psychon Bull Rev 14:363–367. https://doi.org/10.3758/BF03194078

Sturmberg JP, Bennett JM, Picard M, Seely AJE (2015) The trajectory of life. Decreasing physiological network complexity through changing fractal patterns. Front Physiol 6:169

Turvey MT (2007) Action and perception at the level of synergies. Hum Mov Sci 26:657–697. https://doi.org/10.1016/j.humov.2007.04.002

Turvey MT, Carello C (2011) Obtaining information by dynamic (effortful) touching. Philos Trans R Soc Lond B Biol Sci 366:3123–3132. https://doi.org/10.1098/rstb.2011.0159

Turvey MT, Fonseca ST (2014) The medium of haptic perception: a tensegrity hypothesis. J Mot Behav 46:143–187. https://doi.org/10.1080/00222895.2013.798252

Turvey MT, Burton G, Amazeen EL et al (1998) Perceiving the width and height of a hand-held object by dynamic touch. J Exp Psychol Hum Percept Perform 24:35–48. https://doi.org/10.1037/0096-1523.24.1.35

Turvey MT, Shockley K, Carello C (1999) Affordance, proper function, and the physical basis of perceived heaviness. Cognition 73:B17–B26. https://doi.org/10.1016/S0010-0277(99)00050-5

Valk TA, Mouton LJ, Bongers RM (2016) Joint-angle coordination patterns ensure stabilization of a body-plus-tool system in

point-to-point movements with a rod. Front Psychol 7:826. https://doi.org/10.3389/fpsyg.2016.00826

Van Orden GC, Holden JG, Turvey MT (2003) Self-organization of cognitive performance. J Exp Psychol Gen 132:331–350. https://doi.org/10.1037/0096-3445.132.3.331

Van Orden GC, Holden JG, Turvey MT (2005) Human cognition and 1/f scaling. J Exp Psychol Gen 134:117–123. https://doi.org/10.1037/0096-3445.134.1.117

van der Steen MC, Bongers RM (2011) Joint angle variability and co-variation in a reaching with a rod task. Exp Brain Res 208:411–422. https://doi.org/10.1007/s00221-010-2493-y

Waddell ML, Amazeen EL (2017) Evaluating the contributions of muscle activity and joint kinematics to weight perception across multiple joints. Exp Brain Res 235:2437–2448. https://doi.org/10.1007/s00221-017-4979-3

Waddell ML, Amazeen EL (2018a) Leg perception of object heaviness. Ecol Psychol 30:314–325. https://doi.org/10.1080/10407413.2018.1438810

Waddell ML, Amazeen EL (2018b) Lift speed moderates the effects of muscle activity on perceived heaviness. Q J Exp Psychol. https://doi.org/10.1177/1747021817739784

Waddell ML, Fine JM, Likens AD et al (2016) Perceived heaviness in the context of Newton's Second Law: combined effects of muscle activity and lifting kinematics. J Exp Psychol Hum Percept Perform 42:363–374. https://doi.org/10.1037/xhp0000151

Wagman JB, Carello C (2001) Affordances and inertial constraints on tool use. Ecol Psychol 13:173–195. https://doi.org/10.1207/S15326969ECO1303_1

Wagman JB, Carello C (2003) Haptically creating affordances: the user-tool interface. J Exp Psychol Appl 9:175–186. https://doi.org/10.1037/1076-898X.9.3.175

Wagman JB, Hajnal A (2014) Task specificity and anatomical independence in perception of properties by means of a wielded object. J Exp Psychol Hum Percept Perform 40:2372–2391. https://doi.org/10.1037/xhp0000014

Wagman JB, Taylor KR (2004) Chosen striking location and the user-tool-environment system. J Exp Psychol Appl 10:267–280. https://doi.org/10.1037/1076-898X.10.4.267

Wagman JB, Langley MD, Higuchi T (2017) Turning perception on its head: cephalic perception of whole and partial length of a wielded object. Exp Brain Res 235:153–167. https://doi.org/10.1007/s00221-016-4778-2

Wallot S, Kelty-Stephen DG (2018) Interaction-dominant causation in mind and brain, and its implication for questions of generalization and replication. Minds Mach 28:353–374. https://doi.org/10.1007/s11023-017-9455-0

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.