Muscular Torque Can Explain Biases in Haptic Length Perception: A Model Study on the Radial-Tangential Illusion

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Abstract. In haptic length perception biases occur that have previously been shown to depend on stimulus orientation and stimulus length. We propose that these biases arise from the muscular torque needed to counteract the gravitational forces acting on the arm. In a model study, we founded this hypothesis by showing that differences in muscular torque can indeed explain the pattern of biases obtained in several experimental studies.

Keywords: haptics, length perception, radial-tangential illusion, torque.

1 Introduction

Our senses provide us with pieces of information concerning our surroundings. These pieces are not necessarily veridical. If one regards perception as a process in which relevant sensory signals are combined into a single perceptual estimate (e.g., [1]), illusory perception boils down to the blending of (a) biased sensory signal(s) into this estimate (thus causing its non-veridicality). Therefore, to understand an illusion, one has to uncover the source(s) of this biased sensory input.

An example of non-veridical perception in the haptic domain is the radial-tangential (r-t) illusion. For clarity, imagine the top view of a standing person's head as the center of a wheel. The spokes of the wheel indicate the radial directions, with the tangential directions orthogonal to them. In 1954, Reid first showed a bias in the perceived extent of arm movements ([2]). Subsequently, it was shown that the direction of arm movement expressed in trunk-centered coordinates (radial vs. tangential) was fundamental to this bias ([3, 4]): arm movements executed in the radial direction were consistently overestimated, whereas tangential movements were underestimated. Thus, when an observer explores an L-shaped haptic stimulus by sequentially tracing the two legs with a finger, the radial segment (standing leg) is perceived to be shorter than a tangential segment (lying leg) of equal length. For an L-figure to feel 'square', a 13-22% longer tangential segment is required ([5]). This overestimation of radial versus tangential lengths is referred to as the r-t illusion.

Over the past five decades, several studies have identified specific factors that alter the degree of over- or underestimation of haptically perceived length (for a review,

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see [6]). First, the overestimation of a radially orientated segment increases with its length ([7, 8]). Second, the strength of the radial-tangential illusion depends on the type of exploratory movements. Whole-arm movements induce large perceptual biases, whereas finger-and-hand motions alone induce no bias ([7]). Furthermore, for whole-arm movements the strength of the illusion varies with stimulus length (e.g., [7, 8]) and stimulus orientation ([8, 9]).

It has been hypothesized that the described perceptual biases are caused by differences in movement time between radial and tangential movements ([8, 10]). This hypothesis was recently falsified [5]; it was shown that the radial-tangential illusion was not affected by manipulations of movement time. In this study we advance a gravity-related source of sensory information for the biases. By means of a model simulation we will demonstrate that this single source of information can explain that the magnitude of the perceptual bias depends on the geometry of the task.

Sensing the position of one's limbs in space is called kinesthesis. Arm kinesthesis is greatly affected by manipulations of the position of the arm's center of mass (CM) ([11, 12]). Gravitational forces on the arm can be thought of as a single force vector that acts at the CM. The horizontal distance from the CM to the shoulder joint is the moment arm of the gravitational force, and hence it determines the muscular torque that is required to counteract gravity and keep the arm at a constant vertical height. Given the influence of CM position on perceived arm position, it is conceivable that muscular torques are used by the central nervous system as a cue in limb kinesthesis and potentially also in other haptic tasks that involve limb movement ([13, 14]).

Whenever the arm moves in a radial direction, the position of CM changes such that the moment arm of the gravitational force differs between the start en end positions of a movement. Thus, during a radial movement, increasing (or decreasing) muscular torque is required to maintain the arm at a constant vertical height. In contrast, no changes in moment arm and thus muscular torque accompany tangential arm movements. We hypothesized that a difference in torque magnitude between the start and end position of a movement (ΔTorque) might cause biased length perception. More specifically, a positive ΔTorque would bias toward an overestimation of length, and vice versa. In the current study we founded the ΔTorque hypothesis by comparing its predictions with length perception biases as reported in literature.

2 Methods

We built a simplistic model of the arm to obtain predictions from the ΔTorque hypothesis. This model simulated arm movements over haptic stimuli (line segments) of varying length, position, and orientation. Our analysis consists of a qualitative comparison between patterns of biases predicted from the model, with patterns of biases reported in the literature. We will do so for three different studies ([7-9])

The model. The simulated arm consists of two straight body segments (the upper arm and the lower arm plus hand), and two joints (the shoulder and the elbow, see Fig. 1). The two body segments are of equal length. Furthermore, the segments move in the horizontal plane. In other words, the model simulates 2-dimensional arm movement with elevated elbow at shoulder level. Hence, the required hand position fully determines the shoulder and elbow angles. From the simulated arm positions we determined CM positions. Muscular torque was calculated as $m \cdot g \cdot d$, with m representing the total mass of the arm in kg, g the gravitational acceleration (9.81m/s^2), and d the distance in meters between CM and the shoulder (i.e., the moment arm of gravitational force $m \cdot g$). Note that the radial and tangential directions in this model are in fact defined relative to the shoulder rather than the body midline. Yet, when we refer to radial and tangential directions we will do so in the conventional way, that is, with the directions defined relative to the vertical axis of the body.

Model parameters. Calculated values for muscular torque depend on the length and mass of the two body segments. For the current study we used the measures as obtained from one of the authors. Length of the two body segments was 0.26m, body mass 62kg, and the sagittal distance from body midline to the shoulder was 0.17m. We used standard anthropometrical data ([15]) to calculate the CM of the separate body segments.

3 Results

Overestimation of radially oriented stimuli: the effect of stimulus length. The model was simulated tracing a radially oriented haptic stimulus from its proximal to its distal end. We simulated four different stimulus lengths: 7.5cm, 15.2cm, 22.8cm, and 30.5cm, as in Experiment 1 by Wong ([8]; 90º condition in the Horizontal-Front plane). The proximal end was positioned at a distance of 0.12m from the body vertical axis. The model is shown in Fig. 1 with the smallest (left panel) and the largest stimulus (middle panel). The light and dark grey arm represents the start and end orientation, respectively. White circles represent the CM of the separate body segments; grey diamonds represent the CM of the total arm. The dotted lines represent the moment arm of the gravitational force.

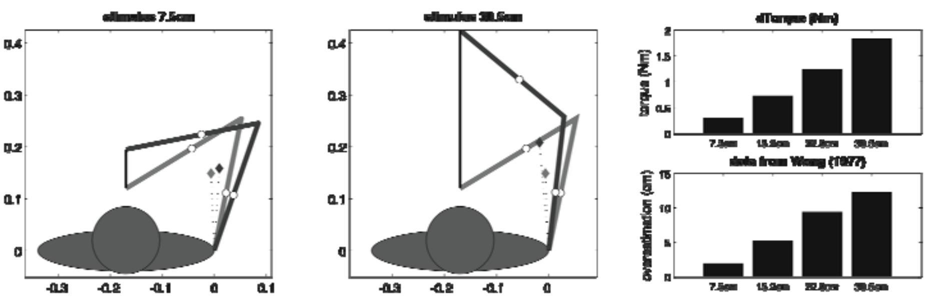

Fig. 1. Model predictions compared with experimental findings for the effect of stimulus length on perceptual biases in haptic length perception. Units on the axis of two left panels are meters.

The forward movement of the hand over the body midline causes the moment arm of the gravitational force to increase. Hence, ΔTorque is positive for these radial movements. The model reveals a pattern of increasing ΔTorque with increasing stimulus length (top right panel), and thus it predicts increasing length overestimation. In line with this prediction, Wong found a pattern of increasingly overestimated stimulus lengths (bottom right panel).

The r-t illusion: the effect of stimulus length. A shape that is generally used to study the r-t illusion is the figure L (e.g., [7]). We simulated the model with an L-figure positioned symmetrically at a distance of 0.3m on the body midline. Absolute values of ΔTorque were calculated because participants in pertinent experiments were often instructed to trace both of the L's legs back and forth. If both movements have an equal ΔTorque, then no difference in biased length perception is expected. Otherwise, the movement with the largest ΔTorque is expected to be overestimated relative to the other.

In Fig. 2, the model is shown tracing a 10.2cm stimulus in the radial (left panel) and tangential (2nd panel) direction. There is a difference in ΔTorque for these two movements (3rd panel), that is, it is largest for the radial movement. Hence it is predicted that the radial leg is overestimated relative to the tangential leg: the r-t illusion. To test the effect of stimulus length on the illusion, we simulated L-figures of 2.5cm, 5.1cm, 7.6cm, and 10.2cm, as in Experiment 3 by Heller and colleagues ([7]; Right Hand, Elbows-Up condition). The model predicts that the magnitude of the illusion will increase with increasing stimulus length (top right panel). This pattern was indeed found experimentally (bottom right panel).

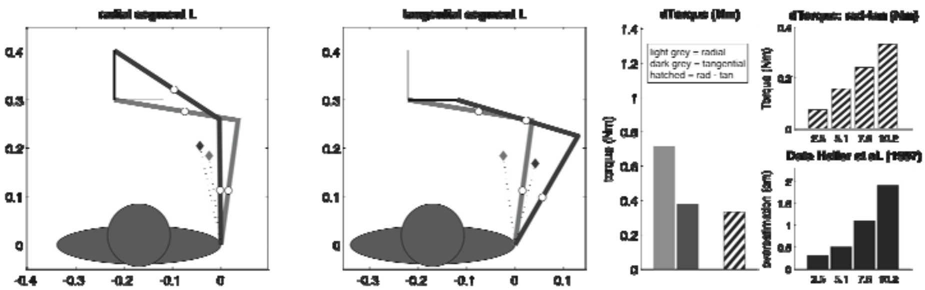

Fig. 2. Model predictions compared with experimental findings for the effect of stimulus length on the r-t illusion. Units on the axis of two left panels are meters.

The r-t illusion: the effect of stimulus orientation. Deregowski and Ellis ([9]) demonstrated that the magnitude of the r-t illusion depends on stimulus orientation. In Experiment 1, they presented an L-figure at 7 orientations: 0 , 15 , 30 , 45 , 60 , 75 , and 90 relative to the body-midline. Thus, for 15 -75 , the direction of the L's legs is a combination of radial and tangential components. A staircase method was used to determine the length at which the standing leg and the lying leg (7.5cm) were perceived equally long. We simulated this experimental setup (see Fig. 3) with a 7.5cm stimulus at a distance of 0.4m on the body-midline. The difference in ΔTorque was calculated for the standing leg minus the lying leg (top right panel). The model predicts a decreasing overestimation of the standing leg's length, and a shift to negative overestimation (i.e., underestimation). More specifically, the model predicts that overestimation changes sinusoidally with the orientation angle. The predicted non-linear pattern of overestimations shows a striking similarity with the experimentally obtained pattern (bottom right panel).

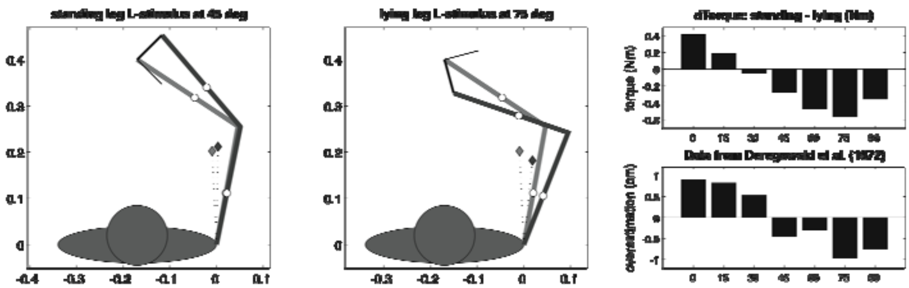

Fig. 3. Model predictions compared with experimental findings for the effect of stimulus orientation on r-t illusion. Units on the axis of two left panels are meters.

4 Discussion

We hypothesized that ΔTorque could explain biases in haptic length perception in general, and the r-t illusion in particular. There was a striking similarity between the ΔTorque patterns derived from our simple arm model and patterns of experimentally obtained perceptual biases. The findings strengthen the hypothesis that the brain uses ΔTorque as a cue in haptic length perception, despite the consequence of biased perception.

Put simply, ΔTorque represents the difference in muscular torque needed to actively counteract gravity at the two endpoints of a movement (i.e., there is no ΔTorque for a supported arm). It is thus a measure of effort. Effort has previously been suggested to relate to biases in haptic length perception ([5, 8, 16]), yet no experimental support was found. Importantly, these authors considered muscular effort in the plane of motion. That is, the torque needed to move the limb against the resistance of its own inertia. This measure mainly depends on the angular acceleration of the movement, whereas ΔTorque depends on the elbow angle (it is the elbow angle that determines the distance between CM and the shoulder). Our current findings revealed that gravity-related muscular effort is a good candidate to account for biases in length perception.

There is a seemingly crucial limitation to our study. The model that we used to calculate ΔTorque was simplified to obtain a unique solution for arm position given stimulus location; we omitted the wrist and considered all movements as if executed in the horizontal plane, which differs from the experiments described. Without any simplification, calculating ΔTorque is a two-dimensional problem in essence. The moment arm of the gravitational force is a vector in the plane spanned by two orthogonal axes that are orthogonal to the gravitational axis (i.e., the horizontal plane). Thus, modeling arm movement with the forearm below shoulder level equals to modeling a shorter upper arm. This will decrease the absolute ΔTorque values but not the patterns that we currently used for comparison with experimental results. Therefore, we believe that the comparisons made in this model study are valid.

This model study has not touched upon all aspects of biased length perception. For example, the r-t illusion was found to be larger for inverted-T-figures than for L-figures (e.g., [9, 17, 18]; but see also [7]). This difference was found to result from the underestimation of bisected stimuli ([18]). We certainly do not exclude that multiple sources of biased information may provide cues for haptic length perception and thus contribute to r-t illusion in haptic length perception as well.

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