

Torques do not influence proprioceptive localization of the hand

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Abstract Because muscle torques counteracting gravity vary systematically during a movement of the arm, it has been suggested that torque differences that occur during a movement provide important information for judging the distance moved away from the body. To test this suggestion, we examined whether external vertical forces applied to the hand (and the torque differences due to these forces) influence proprioception. In a first experiment, the added vertical forces were constant, resulting in a change in torque that was proportional to the gravitational torque, as when holding an object in your hand. This did not affect proprioception. In a second experiment, gradient force fields were used to dramatically change the torque differences. Again, no effect on proprioception was found. Thus, vertical forces caused by hand-held objects do not play an important role in judging the position or movement of the hand.

Keywords Haptics · Psychophysics · Proprioception · Multisensory integration · Hand position sense · Visual localization

Introduction

We are used to a gravitational acceleration of about 9.8 m/s^2 . This makes objects feel heavy and fall down when we do not use enough force to hold them up. From Newton's second law of motion, we know that the force on an object is

the mass of the object times the gravitational acceleration. During movements, the gravitational force on an object is generally constant, because both the mass and the gravitational acceleration are constant. However, the torque, which is the cross-product of the lever-arm distance and the force, changes during our movements. When we make arm movements, the rotation point for the torque is (mainly) the shoulder, so with increasing horizontal distance from the shoulder (extension of the arm), the torque increases. Because we are constantly living in the earth's gravitational force field, one could imagine that we are used to the gravitational force and the torque changes that accompany changes in arm posture and base our movement control on them.

Soechting (1982) was one of the first to study the influence of gravitational torques on proprioception. In his study, he found that a load on one of the arms influenced the variability when matching the elbow angles of both arms. However, based on the same line of reasoning about the influence of torques, Worringham and Stelmach (1985) expected to find a bias instead of an effect on the variability of the matched elbow angle. Therefore, they came up with a more elaborate experiment in which they used loads on both arm, but with a difference of $\pm 5\%$ between the loads (which is below the just noticeable difference threshold). Although Worringham and Stelmach (1985) did not find a significant effect, they strongly speculate that people use relative torque to judge absolute inclination (instead of elbow angle directly) and that torque sensation is an accessory source of information in limb positioning.

Darling and Hondzinski (1999) used horizontal and vertical matching tasks to show that the gravitational torques exerted about the shoulder and elbow did not make significant contributions to sensing forearm-direction relative to earth-fixed axes. Research in parabolic flights showed that

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being in a different gravitational force field induces biases in proprioception and arm movement control (for a review see Lackner and DiZio 2000). With visual feedback or after adaptation to the new forces, these biases disappear (Lackner and DiZio 2000; Fisk et al. 1993). From these findings, and their own data, Ansems et al. (2006) made a distinction between loaded and unloaded movements. They suggest that for position matching in the horizontal plane under load, the brain determines arm position not from the effort required to support the load, but from the effort required to move the load from one position to another (Ansems et al. 2006).

Without loads, Debats et al. (2010) argue that in constant gravity, we use the variations in gravitational torque as a cue for judging the length of our movements. Radial movements give rise to large changes in torque, while tangential movements hardly give rise to any changes in torque, using this cue biases perception. In their study, Debats et al. (2010) modeled the radial-tangential illusion (Debats et al. 2010; Wong 1977; Heller et al. 1997; Marchetti and Lederman 1983; McFarland and Soechting 2007; Deregowski and Ellis 1972; Collani 1979) as the result of differences in torque change between radial and tangential movements. The model fits the trend in the experimental data on the radial-tangential illusions rather well if one assumes that there is a large influence of torque on the perceived position of the hand.

If torques would be an important source of information in proprioception, we would expect large effects of an extra mass in the hand. However, in daily life, we do not seem to have these large effects, e.g., we can put our cup on the table when it is filled with coffee, but also when it is empty. Is this because we use vision to control our movements and compensate for the effects of torque on proprioception, or is proprioception itself not fooled by added mass, for instance because tactile information from holding the extra mass is used to consider the extra mass?

In the present study, we examined whether external vertical forces on the hand influence proprioception. We designed two experiments in which we applied external vertical forces on the hand to test whether changes in torque have an influence on horizontal length reproduction.

Experiment 1

In the first experiment, we examined whether adding constant vertical forces on the hand influences matched positions and the length of movements in the horizontal workspace. We used constant vertical forces of 1N and 2N, in both upward and downward direction. The task was based on the vector-reproduction task that we used in an earlier study with horizontal forces (Kuling et al. 2013). Vectors

in six different directions were used to explore the whole range of movements from radial to tangential (as in Debats et al. 2010; Wong 1977). We expected that radial movements would be reproduced with shorter length than tangential movements, and movements with movement angles in between would be reproduced with lengths that were in between, as in previous studies (e.g., Wong 1977). Extra force downward increases the torque differences, so the extent to which radial movements are shorter than tangential ones is expected to increase.

Methods

In this experiment, we used the same set-up and task as we previously used for testing the influence of horizontal forces on proprioceptive position sense (Kuling et al. 2013). Subjects had to reach visually presented positions with the handle of a force feedback device or to judge a distance and direction visually and reproduce the corresponding vector with the handle (all in the horizontal plane). The force feedback device imposed a vertical force on the subject's hand; the magnitude of the force was independent of the position of the hand (constant force field).

Subjects

Ten subjects (23–34 years of age, one man, three left-handed) volunteered to take part in the experiment. All subjects reported (corrected-to-) normal vision and were naive about the purpose of the experiment. The experiment is part of an ongoing research program that has been approved by the ethics committee of the Faculty of Human Movement Sciences of VU University. All subjects gave their written informed consent.

Stimulus and apparatus

The set-up was the same as in our previous study (Kuling et al. 2013). We projected the visual target stimuli on a horizontal white see-through projection screen above a horizontal mirror. The mirror reflected the images so that the subjects perceived the targets in a plane below the mirror. Subjects moved their hand below the mirror, holding a PHANToM Premium 3.0/6DoF (SensAble Technologies) force feedback device, which was used to create the force fields. Five different vertical force fields were presented in the workspace: null (without forces), upward force fields of 1N and 2N (Up 1N and Up 2N), and downward force fields of 1N and 2N (Down 1N and Down 2N). The forces were constant, independent of the position of the handle.

There were two types of trials: position trials and vector trials [as in Exp.2 of our previous study (Kuling et al. 2013)]. In the position trials, subjects had to move the

handle to a visually presented target position. In the vector trials, the subjects had to move according to a visually presented vector. The vector stimulus consisted of two items: an arrow (length = 1 cm) at the start position, which

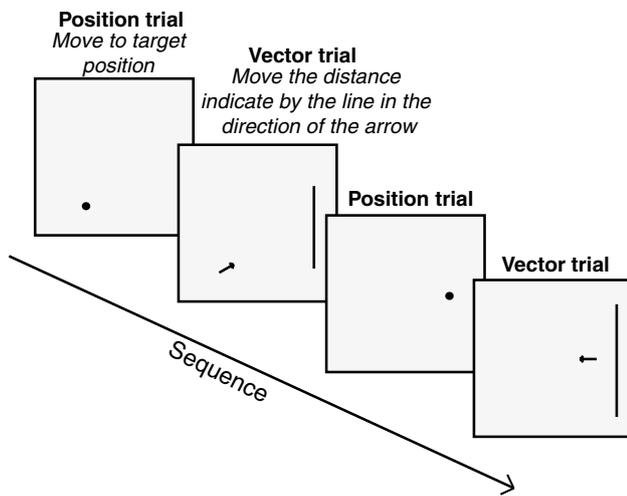


Fig. 1 Example sequence of the task. First subjects had to move to a target position (position trial). Then an arrow and a line were shown, and the subject had to move the distance indicated by the line in the direction of the arrow (vector trial). They then had to move to a new position, and so on

indicated the direction of the vector, and a line on the right side of the projection screen that indicated the length of the vector (Fig. 1). Vector trials were always preceded by a position trial to make subjects start at predefined positions.

There were six target positions, which also served as start positions of the subsequent vector trial. The six target positions were located on a circle with a radius of 10 cm and its center about 30 cm in front of the subject. Each target position was combined with three different vectors, giving a total of 18 pairs of position-vector movements. The chosen vectors were the vector to the nearest counterclockwise neighboring target position (vector length is 10 cm), to the furthest (opposite) target position (vector length 20 cm) and to the second-nearest clockwise neighboring target position (vector length is 17.3 cm). All vectors and the resulting movement directions can be seen in Fig. 2a.

Procedure

Because of the large number of trials (1,440 in total), the experiment was split into two sessions for each subject. Each of the five force fields was presented as a block of 144 trials (72 position trials and 72 vector trials) in each session. It took subjects about 5 min to complete a block of trials. After each block, there was a break of about 3 min. A

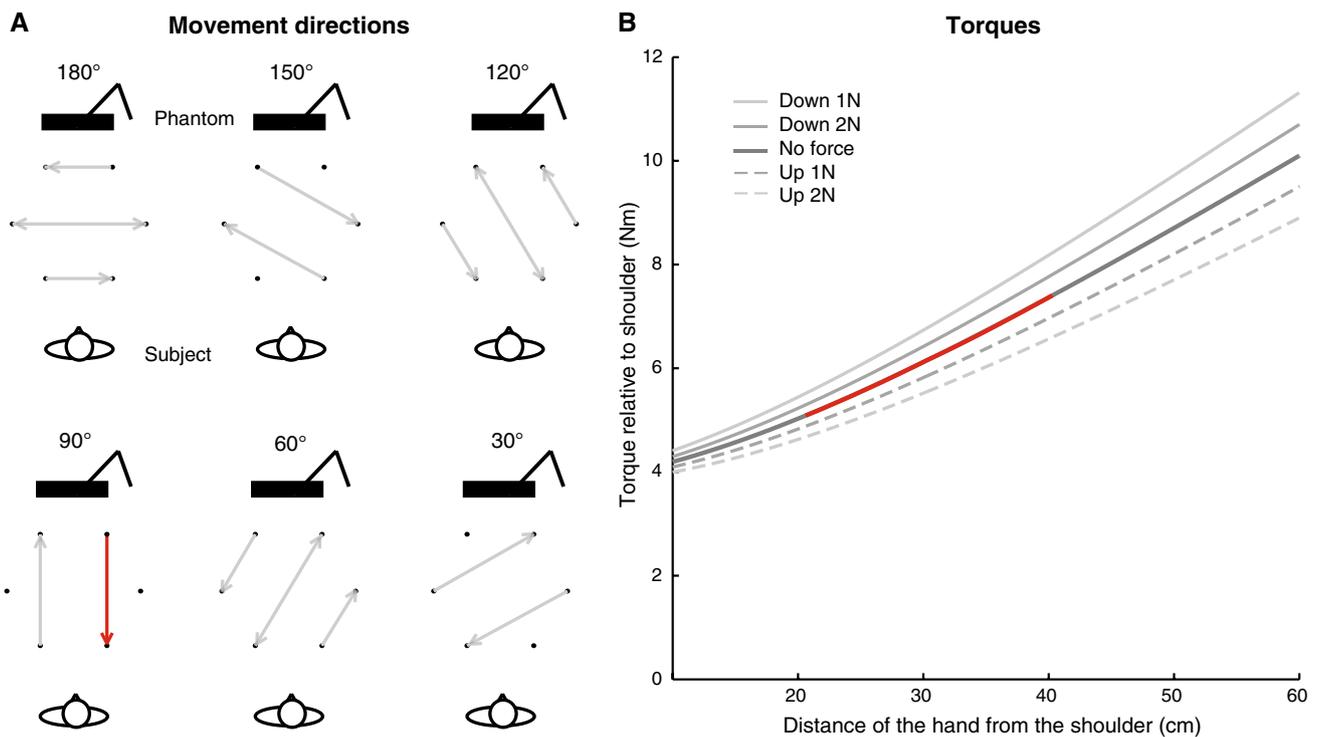


Fig. 2 Methods of Experiment 1. **a** The specific movements that were used (subjects and PHANToM are not drawn to scale). **b** Relation between shoulder torque and distance between the hand and the shoulder for a standard human arm for different constant forces on

the hand. The red movement in **a** (lower left panel) without forces corresponds with a change in torque on the hand according to the red part of the central curve in **b** (color figure online)

session therefore took about 40 min. The two sessions were performed on different days within a two-week period. The force fields were presented in a counterbalanced order across subjects. Within each block, each pair of target position and vector was presented four times. Trials were presented in random order, with the exception that there were never two identical position-vector pairs in a row.

The subjects received verbal instructions about the task. The block started with a target appearing. Subjects had to move their hand to the position at which they perceived the target. When they were satisfied about the position, they pressed the button on the PHANToM and vector information appeared. They had to move in the direction of the arrow by the distance that the line length indicated. When they were satisfied, the subjects had to press the button again, and a new target appeared. Subjects did not receive any feedback during the experiment other than from their own proprioception. The position of the subject's hand was tracked by the PHANToM during the whole experiment.

Analysis

We anticipated that the force fields' influences on proprioception would be proportional to the cosine of the elbow angle, which mainly varies when moving in the radial direction. To calculate the ratio of reproduced vector lengths per subject, vector and force field, the distance between the start and end position of each vector trial was taken. This value was divided by the visually presented length, and the resulting length ratios were averaged for each of the six possible directions of the movement paths and compared over directions and force fields. The reproduced vector lengths were analyzed with a 5×6 RM ANOVA (force field \times movement direction). If sphericity was violated, Greenhouse-Geisser correction was used. The torque differences were calculated for each trial and subsequently averaged for each vector, force field and subject.

If an average person (anatomical data of Winter 1990) would exactly reproduce the presented vectors, we expect an increase of the torque differences of 8.0 % per added Newton downwards force for the radial movements. To keep the changes in torque during the movement equal in all the force fields, the moved distances would decrease (increase) by 8.0 % for the Down (Up) 1N force field and by 16.0 % for the Down (Up) 2N force field. Figure 2b shows the relation between the torque and the distance between hand and shoulder for an average person in the different force fields.

Besides an effect on the reproduced length in the radial direction, one might expect a shift of all positions toward (away from) the subject's body for the downward (upward) force fields due to increased (decreased) torque. Therefore, the mean end points of the position trials were calculated

for each subject and force field and analyzed by fitting a translation (a uniform shift of the endpoints) of the complete pattern of end points to the data (as in Kuling et al. 2013).

Results

Individual subjects had different biases between visually presented length and length reproduced with the hand, in line with earlier studies [e.g., Kuling et al. 2013; Rincon-Gonzalez et al. 2011; Smeets et al. 2006; Sousa et al. 2010]. In general, subjects moved longer distances than the visually presented lengths. Only one subject made movements that were shorter than the visual lengths.

The length ratios can be seen in Fig. 3a. They depend on movement direction, but no difference can be seen between the force fields. The ANOVA on the length ratios showed a main effect of movement direction ($F_{2,7,23,9} = 3.54, p < .05$), but no main effect of force field ($F_{4,36} = .79, p = .54$) and no interaction effects ($F_{5,1,46,2} = 1.10, p = .37$). Post hoc comparisons showed that the classical radial-tangential illusion was present; tangential movements (180°) were significantly longer than approximately radial movements (90° and 120°).

The mean torque differences due to the movements that the subjects made in the different force fields were larger for the downward forces than without extra forces; 1N and 2N downward forces gave a mean overall increase in torque difference of 11.3 and 25.9 %, respectively. For the upward forces, the torque differences were 6.6 % (Up 1N) and 18 % (Up 2N) smaller than without extra forces. If subjects had maintained the torque differences for the different movement directions (Fig. 3b), rather than movement length, the latter would have varied systematically in radial direction. There is no indication of a trend in this direction.

To test whether there was an overall shift of the end points due to the force fields, the mean end points of the end point trials were determined for each subject and force field. The best fits of uniform shifts between the end points with and without forces were determined. The parameters of the best fits can be seen in Fig. 4. Each dot represents the fit of one subject in one force field. The ellipse is the 95 % confidence ellipse of the mean, calculated by dividing the axes of the 95 % confidence ellipse of the distribution by the square root of the number of data points (which is twice the number of subjects because the data points of 1N and 2N are treated independently). For both upward (left panel) and downward (right panel) forces, the origin lies within the 95 % confidence ellipse of the mean, which means that the shifts are not significantly different from no shift. Thus, altogether the end points in the force fields are not systematically different from those without forces.

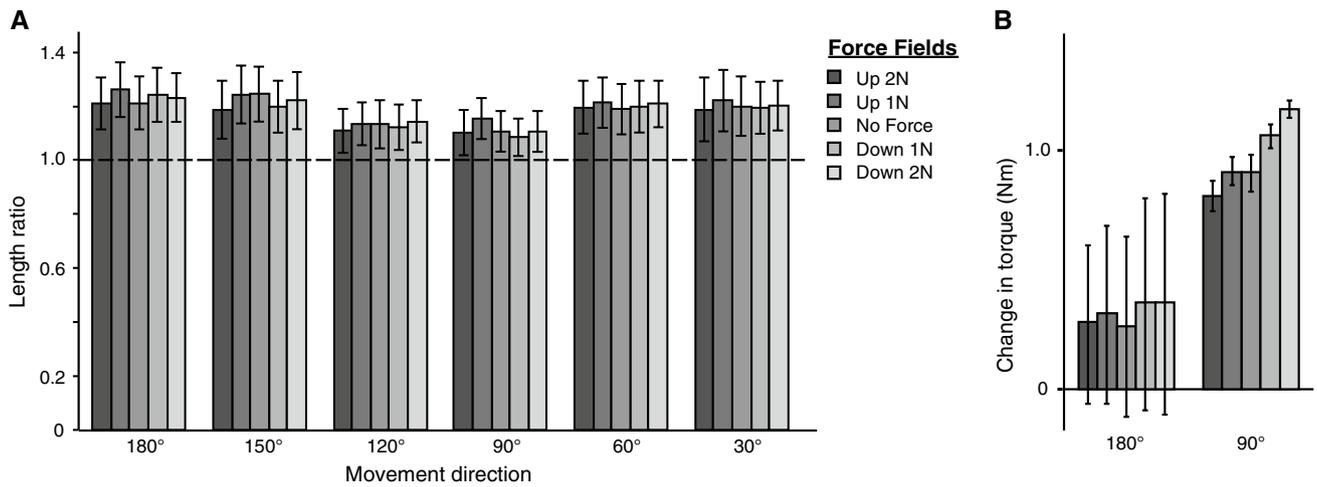
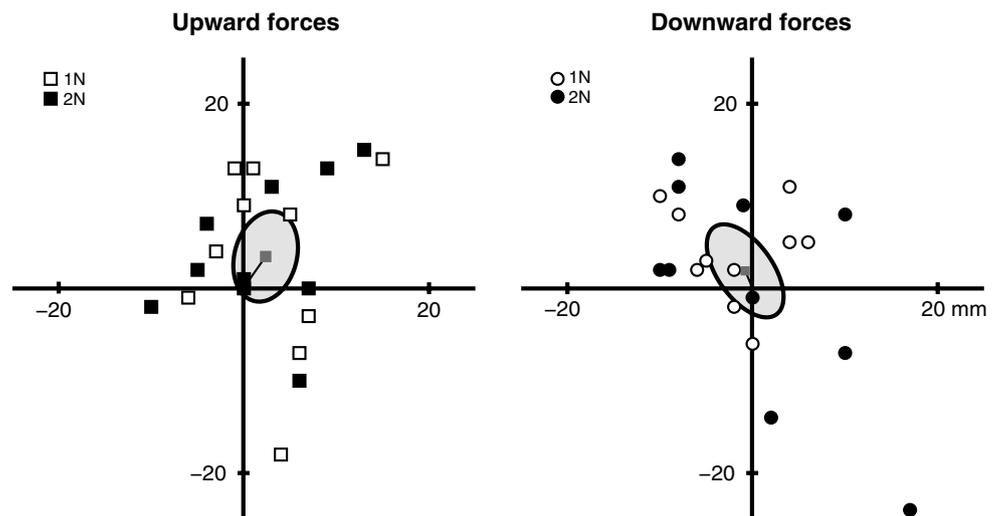


Fig. 3 Results of Experiment 1. **a** The length ratio as a function of movement direction. The different gray tones indicate the different force fields. **b** Mean changes in torque caused by the different force fields and two movement directions. Error bars show standard errors

across subjects. The systematic effect of force fields for the radial (90°) movements shown in **b** is not present in the data in **a**, indicating that the predicted effect of torque change on length ratio is absent

Fig. 4 Effect of force fields on the end points of position trials. The translation pattern of the end points between the no force and the force field conditions. All axes show translation in mm. The symbols show the results per subject for the force fields of 1N (open) and 2N (filled). The gray squares show the mean translation over both force strengths. In both upward force fields (left panel) and downward force fields (right panel), the origin falls within the 95 % confidence ellipse of the mean of the distribution of translations (see text for details)



Discussion

The length of the produced movements show the pattern that is typically found in studies with the radial-tangential illusion: the radial movements are shorter than the tangential ones for the same desired displacement (Wong 1977; Heller et al. 1997; Marchetti and Lederman 1983; McFarland and Soechting 2007; Deregowski and Ellis 1972; Colnani 1979). However, we were more interested in whether force fields could change this pattern. We expected, based on the model of Debats et al. (2010), that increasing the torque differences during a movement would decrease the amplitudes of these movements. The results show that the lengths did not differ between the force fields, while the torque differences differed significantly. Furthermore, the

force fields did not induce an overall shift of the position of the arm in the workspace.

Subjects clearly do not rely on changes in torque to the extent predicted by the model of Debats et al. (2010). The torque differences in our experiment might have been too small to reveal more modest differences between the reproduced lengths. Moreover, subjects may have correctly adjusted to the additional forces because the downward forces correspond with moving their arm while holding something in their hand. To distinguish between these possibilities, we designed a second experiment with gradually increasing (or decreasing) downward forces to exaggerate the normal torque differences during the movements, to see whether larger torque differences would influence the reproduced vector lengths.

Experiment 2

In the second experiment, the magnitudes of the vertical forces were position dependent (in the radial direction), and therefore, torque difference increased much more or less with radial distance than in Experiment 1. If the perceived extent of the movement is influenced by the change in torque, radial movements will change when these forces are applied, while the tangential movements will remain the same.

Methods

Subjects

Twelve subjects (two left-handed, four men, 23–59 years of age, mean age 30 years) volunteered to take part in the experiment. All subjects reported (corrected-to-) normal vision and were naive about the purpose of the experiment. Four of the subjects had taken part in Experiment 1. All subjects gave their written informed consent.

Stimulus and procedure

The apparatus and task were identical to those in Experiment 1, but the force fields, target positions and vectors differed (Fig. 5a). We used three force fields: no force,

increasing gradient (force pushing upwards close to the body and pushing downwards further away), and decreasing gradient (force pushing downward close to the body and pushing upwards further away). In the latter two force fields, the forces were zero about 30 cm in front of the subject's body (the center of the workspace). The forces changed with the distance from the body by 25 N/m in the radial direction and were independent of the tangential and vertical position of the handle. The relation between total shoulder torque and distance can be seen in Fig. 5b.

To concentrate on the radial/tangential differences, we only used radial (perpendicular to the subject's body) and tangential (parallel to the subject's body) movements. From each of four target positions, two different vectors could be presented. All vectors had the same length; 15 cm. Note that the visual vectors were shorter than the distances between the target positions (20 cm), to get clearly different endpoints for position and vector trials. The eight position-vector pairs were each presented eight times. The three force fields were presented in different blocks within one session. Each block had 128 trials. The force fields were presented in a counterbalanced order across subjects. Trials were presented in random order, with the exception that there were never two identical position–vector pairs in a row.

The verbal instructions about the task were the same as in Experiment 1, and again the position of the

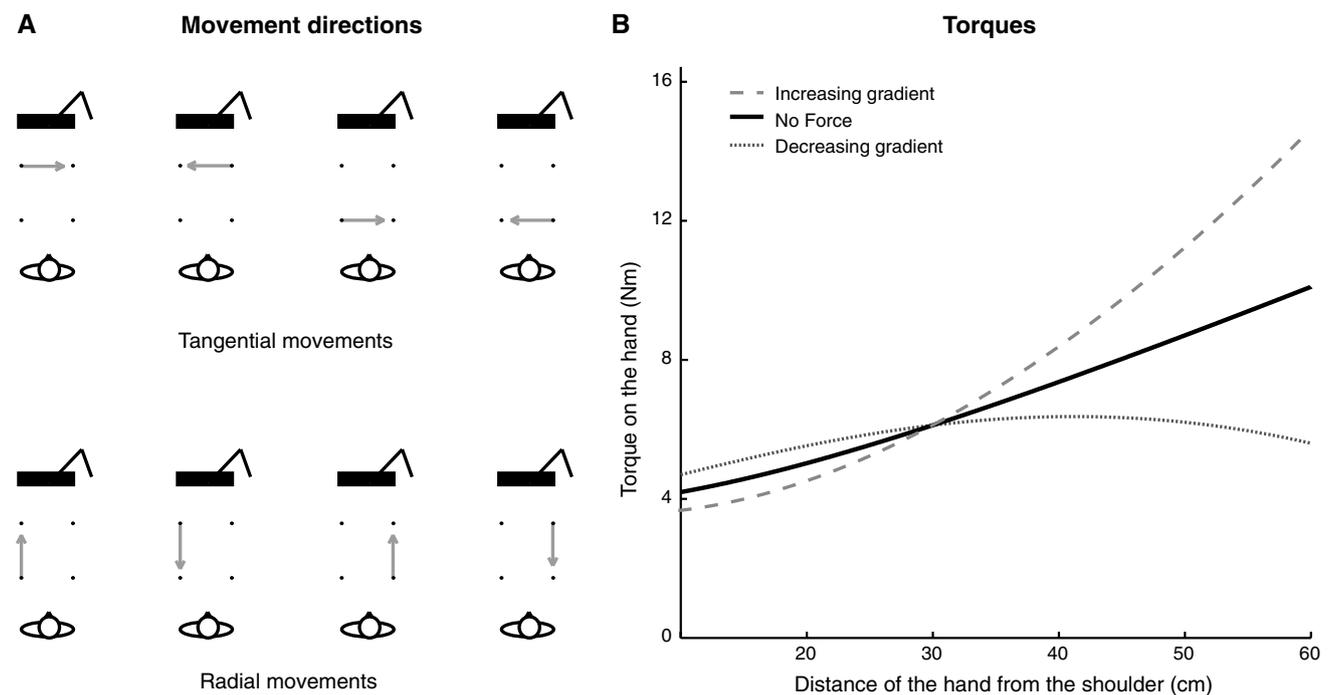


Fig. 5 Methods of Experiment 2. **a** The specific movements that were used for the radial and tangential directions (subjects and PHANToM are not drawn to scale). **b** Relation between shoulder

torque and distance between the hand and the shoulder for standard human arm postures for the different forces fields on the hand. Note the different *vertical scale* in this figure than in Fig. 2b

subject's hand was tracked by the PHANToM during the whole experiment. The experiment took about 20 min. As in Experiment 1, the mean lengths and torque differences of the reproduced vectors were calculated per subject, vector and force field. The length ratios were analyzed with a 3×2 RM ANOVA (force field \times movement direction), and if necessary Greenhouse-Geisser corrections were used.

Results

As in Experiment 1, the reproduced vector lengths were in general longer than the presented lengths (Fig. 6a). The ANOVA showed no main effect of movement direction ($F_{1,0,11.0} = 1.95$, $p = .19$), no main effect of force field ($F_{1,3,14.7} = .63$, $p = .48$), and no interaction effects ($F_{1,3,14.3} = 1.02$, $p = .35$). Although a trend can be seen in Fig. 6a, the radial movements were not significantly shorter than the tangential movements, in contrast to the results of Experiment 1. The mean changes in torque were very different in the different force fields (Fig. 6b). For the radial vectors, the changes in torque were about doubled or reduced to zero, while for the tangential vectors, the changes in torque were similar for all force fields (Fig. 6b). The length ratios do not appear to be influenced by the differences in torque changes (Fig. 6a).

Discussion

In Experiment 2, we again found that the position-dependent force fields did not influence the lengths of the vectors that subjects reproduced. Although the torque differences were doubled or reduced to zero by the added forces, the lengths did not change at all. The subjects did notice that

moving in some force fields cost more effort than moving in others (self-report), which indicates that these force fields were felt. We thus conclude that external forces on the hand do not influence proprioception.

General discussion

In this paper, we described a set of experiments in which we tested the hypothesis that changes in shoulder torques influence the judged length of human arm movements (Debats et al. 2010). We manipulated the torque differences, but did not find any effects on the length of the movements. These results are in line with earlier studies that did not find biased results of external loads on the arm (Worringham and Stelmach 1985; Darling and Hondzinski 1999). We did not find differences between loaded and unloaded conditions as others suggested (Soechting 1982; Ansems et al. 2006).

The haptic radial-tangential illusion has been measured in various ways. Two commonly used methods are 2-AFC tasks (subjects choose whether the radial or the tangential component is longer) (Debats et al. 2010; Wong 1977; Heller et al. 1997; Marchetti and Lederman 1983; McFarland and Soechting 2007; Deregowski and Ellis 1972) and reproduction tasks (one segment is felt and has to be reproduced in the other direction) (Collani 1979). Neither method involves visual information. In our study, we presented vector lengths visually and asked subjects to match these by moving in different directions. In Experiment 1, we found the same pattern in reproduced lengths as in a 'classic' haptic radial-tangential experiment, which suggests that the method itself is not critical. However, in Experiment 2, this radial-tangential effect was not clearly present, which might suggest that the illusion is not as strong when visual information plays a role as when presented purely haptically. Another possibility could be that in Exp. 2, subjects gave the torque information less weight in judging the distance because of the unusual external forces.

Although we manipulated shoulder torque, there might have been small changes in wrist torque and elbow torque. However, because of the subjects' posture (we asked the subjects to hold the handle of the device in power grip and to keep the handle vertical), the torque changes of the elbow and wrist due to the movement were limited. Holding the handle in a power grip has been shown not to influence precision or accuracy (Kuling et al. 2014).

In both Experiment 1 and 2, we found that torque differences caused by external vertical forces did not influence the lengths of the arm movements. These findings are good news for the use of powered exoskeletons and robotic lifting aids [e.g., (Perry et al. 2007)], because they suggest that the forces added by the devices, to overcome the weight of

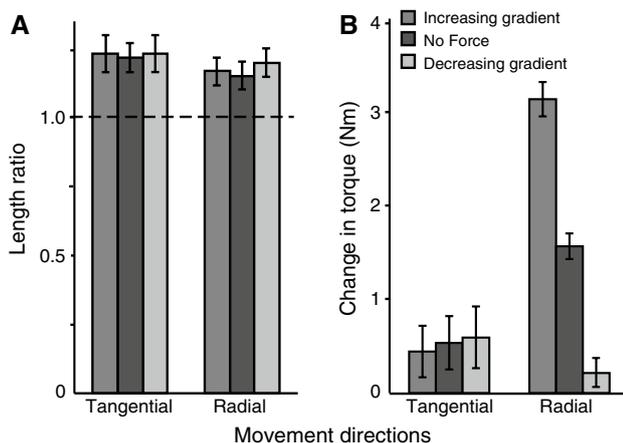


Fig. 6 Results of Experiment 2. **a** Mean distance moved for the different directions and force fields. **b** Mean changes in torque for the different movements. Error bars show standard errors across subjects

the device and to help perform the task, will not change the user's movements. In an earlier study (Kuling et al. 2013), we showed that horizontal force fields do not disturb the end points of a movement, or the length of a reproduced vector, either.

An important difference between the added external forces that we used and the natural gravitational force is that our external forces can be felt on the skin, while the gravitational forces cannot. The effect of changes in gravitational force in parabolic flights, but not in our study and other studies that used forces and loads, suggests that humans can compensate for additional forces and torques on the hand, but not for changes in torque due to changed gravitational forces. This might be because of the presence of tactile information of the forces and loads. The tactile information might give people information about the part of the torque that comes from the object in the hand or might lead to a reduction of the weight that subjects give to torque change as cue for movement length.

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