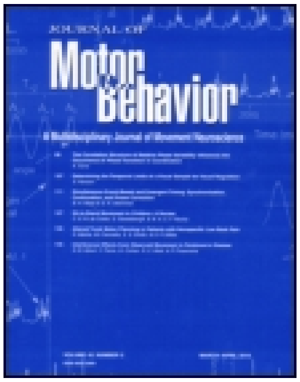

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RAPID COMMUNICATION

Haptic and Visual Influences on Grasp Point Selection

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ABSTRACT. When using precision grip to pick up objects, there are many possible pairs of grasp points that permit the thumb and index finger to exert opposed forces for secure grip. Previously, it was shown that individuals select grasp points so that the line between them (grasp axis) passes through or near the center of mass (CoM), thus minimizing the torque around the grasp axis during lifting. The accuracy of grasp axis selection depended on object spatial symmetry, indicating the importance of vision. The authors investigated how grasp point selection is influenced by haptic as well as visual information. Ten participants lifted cuboids whose CoM was located either symmetrically in the geometric center or asymmetrically toward one end. Results for the asymmetric cuboid revealed that grasp points migrated toward the asymmetric CoM from the geometric center. This was more pronounced in the presence of visual cues that reliably indicated the location of CoM. The results suggest that grasp point selection is influenced by a multimodal representation of CoM.

Keywords: center of mass, hand, haptic perception

In lifting an object using precision grip with opposed index finger and thumb, grip force normal to each contact surface allows the development of frictional resistance to vertical load force, tangential to the surface, due to the weight of the object. To prevent the object from slipping, the product of the grip force and the coefficient of friction between the digits and the object must exceed the load force. It has been shown that when manipulating a familiar object grip force increases in parallel with load force and the rate of force increase scales with object attributes including the weight and coefficient of friction (Johansson & Westling, 1984; Westling & Johansson, 1984). During predictable lifts, grip force rises slightly before load force; this anticipation is taken to reflect the operation of a forward internal model in the control of movement (Flanagan & Wing, 1997). An unexpected change in surface friction or weight between trials results in feedback corrections to rescale grip force on that trial, and the anticipatory control mechanism may adapt the grip force to the new conditions over the next one or two trials (Flanagan, Bowman, & Johansson, 2006).

Although much research has concerned individuals' ability to predictively adjust the grip force in response to factors destabilizing their grip, prehension strategies are not limited to selection of an appropriate grip force. An alternative option involves positioning of the digits on the target object to reduce the grip force required for stable grip on the object. These grasp points are particularly important when the mass distribution of the object is considered. For instance, when lifting and moving an object using precision grip, the nature of the load also changes depending on the location of the center of mass (CoM) relative to the grasp axis between the thumb and index finger. Imagine a task in which a person holds a rectangular object stationary in the air using precision grip (Figure 1A). The object experiences downward force due to gravity acting through the CoM of the object. When the grasp axis departs from the object's CoM in the longitudinal direction, a torque develops around the grasp axis. On the other hand, when the object is supported with grasp axis through its CoM, there is no torque around the grasp axis and the individual only needs to support the mass of the object against gravity. Previous studies have shown that the CNS predictively scales grip force to compensate for the torque due to increased distance between the grasp axis and CoM (Goodwin, Jenmalm, & Johansson, 1998; Jenmalm, Goodwin, & Johansson, 1998; Wing & Lederman, 1998; for review, see Wing & Lederman, 2009). Furthermore, it has been shown that individuals modify multidigit grip to minimize the total force used in counteracting an externally induced torque (Fu, Zhang, & Santello, 2010; Lukos, Ansuini, & Santello, 2007). These latter studies focused on biomechanical optimality of the forces used as a function of object dynamics. However, they did not seek to elucidate whether individuals respond to changed object dynamics (presence of torque) by changing grasp location and that is the focus of the present study.

In principle, CoM can only be known through physical interaction with the object. However, if it can be assumed that the object has a uniform distribution of mass, visual information can provide an estimate of CoM as the geometric center of the object coincides with CoM. Such visual information is likely to be most useful as a cue when there has been no prior contact with the object. Indeed, it has been show that individuals favor a grasp axis near the geometric center when they are free to choose their grasp points on objects with uniform distribution of mass (Lederman & Wing, 2003). However, the extent to which grasp point selection is made on the basis of visual and haptic information remains unclear. The aim of the present study was to investigate two questions. First, do individuals seek to avoid torque when selecting grasp positions for stably supporting an object? Second, if so, how do congruent or conflicting visual and haptic cues concerning CoM determine grasp points?

Method

Participants were 10 volunteers (4 men and 6 women; M age = 23.90 ± 2.23 years) who were paid £6 for their

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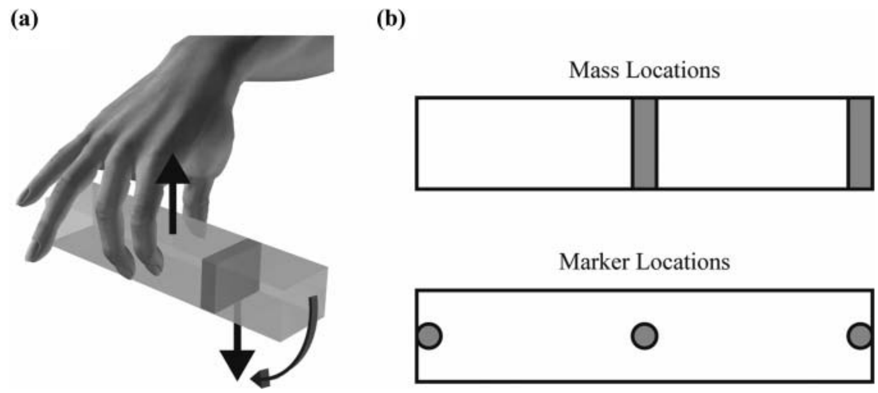

FIGURE 1. (**A**) A schematic illustration of the grip configuration and forces acting on the object. To support an object in the air, the individual has to apply a force in the upward direction equal to or higher than the downward gravitational force, as indicated by the two straight arrows. When the lines of action of these two forces are different in the longitudinal axis of the object, a torque develops (curved arrow). (**B**) Possible locations of the external mass and markers as the object were viewed from above. The markers were visible to the participants but the external masses were hidden inside the object.

participation in the study. All were right-handed, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971), and had normal or corrected-to-normal vision by self-report. The participants were naive as to the purpose of the experiment and gave informed consent prior to participation. The experimental procedure was approved by the Bangor University ethics committee and complied with the Declaration of Helsinki.

Each trial involved one of six objects, which were plastic cuboids (170 × 35 × 15 mm, weight 20 g) covered with matte black paper. A 60-g mass was concealed at the center or at one end of the object resulted in a symmetric (centrally located CoM) or asymmetric (CoM shifted 52.5 mm from the center toward one end) location of CoM (Figure 1B). The asymmetric CoM caused a noticeable torque when the object was grasped and lifted with the grasp axis passing through the geometric center. In selected conditions, a surface mark provided a visual cue to CoM location. In separate blocks this cue was either reliably aligned with the location of the concealed mass across trials or unreliably indicated the mass location (being placed 50% of the time at the end where the mass was located and 50% at the geometric center).

Participants were seated at a table to perform the task. An object was placed 50 mm in front of the participant and aligned with the participant's right shoulder. The participant was asked to grasp the object and transport it to a target location 300 mm in front of the starting position using the thumb, index, and middle fingers of the right hand. The participant was allowed to grasp anywhere on the object but encouraged to prevent the object from tilting while transporting it. The start of a trial was verbally cued by the experimenter and there were no time constraints. At the end of each trial, the experimenter carefully moved the object with two hands to the starting position so it would not provide the participant with cues to CoM by visual observation. Neither the location of CoM nor the hypothesis of the experiment was disclosed to the participant throughout the study. Before testing, the participants were allowed to practice the task using a symmetric object of different size and weight from the set of test objects.

Reflective markers were placed on the object and the nail beds of the thumb, index, and middle fingers to record the grasp points using a two-camera ProReflex motion tracking system (Qualisys, Gothenburg, Sweden). Two markers on the objects were placed on the lateral ends of the object. The kinematic data were first smoothed with a second-order bidirectional Butterworth low-pass filter (10 Hz cutoff). The longitudinal positions of the digits on the object were determined for the initial phase of lifting the object, characterized by the first time at which the object marker vertical velocity exceeded 10 mm/s. The distance of each digit from the object geometric center was then calculated.

This was a 2 × 3 × 10 within-participants design. The first independent variable was mass distribution of the object, which was symmetric or asymmetric. The second independent variable was visual cue about the mass location that was either reliable, unreliable, or absent. The reliable cue correctly indicated the location of the external mass inside the object, whereas the unreliable cue changed the location of the visual marker on every trial across the three possible locations. The order of the three visual cue conditions was randomly assigned with symmetric and asymmetric CoM locations alternating for each cue condition. The third independent variable was trial number. Each participant performed 10 trials per condition, giving a total of 60 trials.

In the present study, a tripod grasp (thumb opposed by the index and middle fingers) was used. Using two fingers affords redundant solutions for how to counteract forces

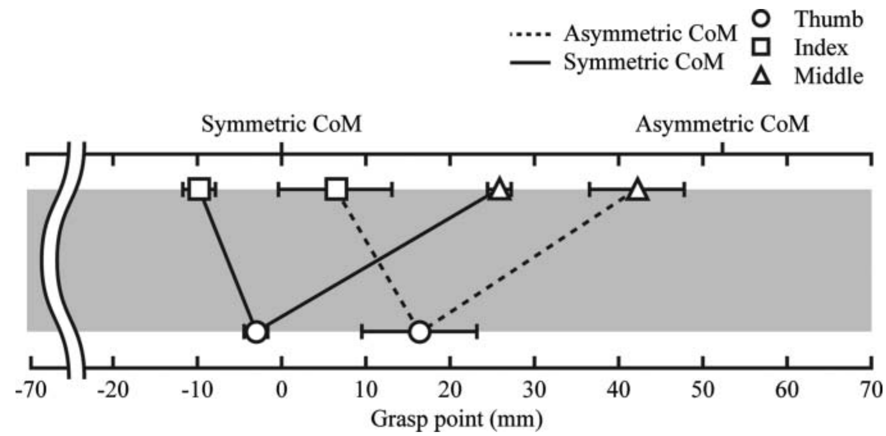

FIGURE 2. Grasp points on the object viewed from above. Grasp points of each digit for objects with asymmetric and symmetric mass distributions were averaged across participants. The zero in the scale indicates the geometric center of the object in the object's longitudinal axis. Because the index and middle fingers are positioned across the geometric center of the object (position = 0) in symmetric CoM, the index finger position has a negative value. The error bar represents 1 *SD*.

either by modifying the force or position of each digit. Indeed, a previous study demonstrated that participants spread the positions of the fingers to more efficiently counteract the rotation of the object (Fu et al., 2010). Nonetheless, our data indicated that the index finger position was highly correlated with that of the thumb ($r = .931$, $p < .0005$) and middle finger ($r = .939$, $p < .0005$). Therefore, only the index finger positions were analyzed using three-way (CoM location vs. visual cue vs. trial) repeated measures analysis of variance (ANOVA). Paired-sample t tests were used for post hoc comparisons when required. An alpha level of .05 or less was employed to quote a statistical significance for all statistical tests.

Results

Figure 2 depicts the mean digit positions for the symmetric and asymmetric CoM locations with the object viewed from above. The digit positions spanned CoM for the symmetric CoM with the index finger being placed close to CoM (8.3 $\pm$ 19.0 mm). In contrast, they did not cover CoM for the asymmetric CoM, although a shift toward CoM was evident (6.0 $\pm$ 6.1 mm). The ANOVA confirmed this shift was statistically significant, $F(1, 9) = 5.08$, $p = .05$. Nonetheless, the grasp point shift due to CoM (16.2 mm) was considerably less than the shift of CoM location (52.5 mm). Although no main effect of visual cue was found ($p = .29$), there was a significant CoM location by visual cue interaction effect, $F(2, 18) = 6.00$, $p < .01$ (Figure 3). The interaction was due to the effect of CoM observed when visual cue was reliable ($p > .03$) and absent visual cue ($p = .05$), but not when visual cue was unreliable ($p = .199$).

Figure 3 depicts changes in grasp points across trials. The ANOVA indicated that there was no main effect of trial ($p = .13$), but there was a reliable interaction between CoM and trial, $F(9, 81) = 3.84$, $p < .0005$. In general, there was a tendency for the grasp points to be at around the center of the object on the first trial across conditions. When visual cue was absent or reliable, the grasp point shifted to toward the location of CoM for asymmetric CoM during the first two trials. With the symmetric CoM, little change was observed across trials. Pairwise comparisons revealed that the separation of the grasp points due to the location of the CoM became statistically reliable from Trial 2 onward for absent visual cue ($p < .02$). For reliable visual cue, the first statistically significant separation of grasp points for the two CoM locations was observed at Trial 5 ($p < .04$). In contrast, the separation of grasp points for the two CoM locations failed to attain significance for the unreliable visual cue.

No interaction effect between visual cue and trial ($p = .93$) or three-way interaction ($p = .46$) was observed.

Discussion

In the present study we investigated how haptic and visual information concerning an object's CoM influences grasp points used in lifting and translating an object. The results extend the findings of Lederman and Wing (2003) and show that grasp points are influenced not only by visual, but also by haptically defined CoM. In the presence of a visual cue to CoM, the shift of the grasp points changed with cue reliability. Because the unreliable visual cue moved between the true mass location and the geometric center in the asymmetric CoM, it could be speculated that the smaller shift of the grasp points toward the asymmetric CoM is due to the attentional modulation of the visual cue that attracted the gaze of the participants and their reach toward the foveated location. Such observations of gaze-dependent reaching control

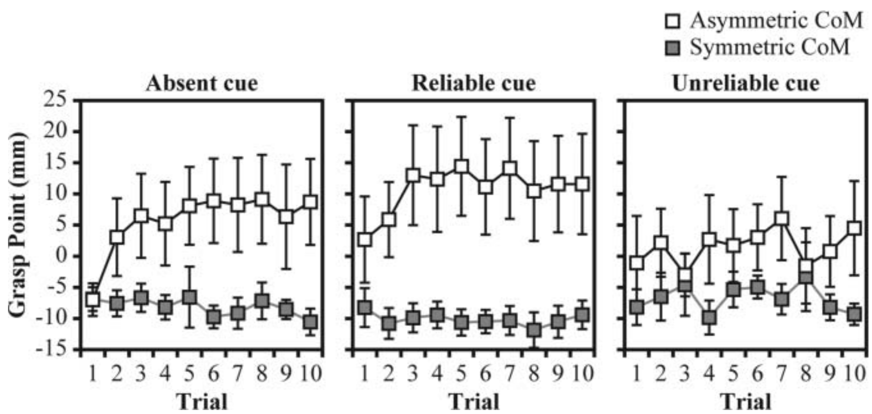

FIGURE 3. Change in grasp points across trials. The error bars represent 1 *SD*.

have previously been made in a study with parietal patients (Jackson, Newport, Mort, & Husain, 2005). Alternatively, the participants may have chosen to grasp the object at the middle section, reflecting the average location of the visual cue traversing between two points. Nevertheless, the effects of the visual cues were relatively small when the mass distribution of the object was symmetric, suggesting that attentional modulation of the visual cue or choosing the average of two visual cue locations cannot fully account for this phenomenon.

When the participants grasped the asymmetric CoM object, they placed the digits between the true CoM and the geometric center of the object. Thus, the rotation due to off-axis grip in the asymmetric CoM condition could have been prevented by either changing the grasp point or increasing the grip force. In our paradigm, the participants might have determined that increasing the grip force was a preferred solution for stabilizing the object rather than shifting the grasp points, especially because the tripod precision grip used in this experiment was better suited to counteracting rotation than two-point precision grip with the thumb and index finger. Another possibility is that participants might have varied the manner in which they distributed force over the two fingers. For example, in the asymmetric condition as well as shifting the grasp points, participants might have increased their reliance on the index finger to oppose the force applied by the thumb. Because we employed a kinematic measure, a resultant force applied by the index and middle fingers could not be directly measured. Future researchers should investigate possible changes in relative contributions of the individual digits in this task, although previously it has been shown in another task that force coordination patterns across the digits are rather limited (Latash, Gelfand, Li, & Zatsiorsky, 1998). An alternative account of the incomplete shift of grasp points toward the true CoM may indicate a bias toward the visually defined geometric center, perhaps due to greater perceived reliability and familiarity of visual information for inferring CoM acquired over the course of life (Gentilucci, 2003).

Previously, it was shown that an accurate internal model of an object can be acquired by lifting the object once or twice, which allows the development of anticipatory grip force control (Flanagan et al., 2006). In our study, the grasp points reliably distinguished asymmetric and symmetric CoMs over 2–5 trials. Given a relatively slower time scale for the grasp point change compared with the grip force modulation reported by Flanagan et al., it suggests that kinematic and kinetic aspects of grasping are processed independently.

In summary, the observed differences in the grasp point following the change in the location of CoM and associated visual cue type allowed us to infer that the grasp points are driven by visual and haptic information about mass distribution of the object.

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