Exp Brain Res (2017) 235:2821–2827
DOI 10.1007/s00221-017-5016-2

RESEARCH ARTICLE

Smooth at one end and rough at the other: influence of object texture on grasping behaviour

Catharina Glowania[1] · L. C. J. van Dam[1,4] · E. Brenner[2] · M. A. Plaisier[2,3]

Received: 1 March 2017 / Accepted: 17 June 2017 / Published online: 21 June 2017
© Springer-Verlag GmbH Germany 2017

Abstract When picking up objects using a pinch grip, there are usually numerous places at which one could place the thumb and index finger. Yet, people seem to consistently place them at or close to the centre of mass (COM), presumably to minimize torque and therefore the required grip force. People also prefer to grasp objects by parallel surfaces and ones with higher friction coefficients (rough surfaces), to prevent the object from slipping when they lift it. Here, we examine the trade-off between friction and COM. Participants were asked to grasp and lift aluminium bars of which one end was polished and therefore smooth and the other was rough. Their finger positions were recorded to determine how they grasped the objects. The bars were oriented horizontally in the frontal plane, with the centre aligned with the participants' body midline. The bars varied in the horizontal offset between the COM and the edge of the rough region. The offset could be 0, 1 or 2 cm. We expected participants to grasp closer to the rough area than the centre of the bar. Completely rough bars and completely smooth bars served as control conditions. The slipperiness of the surface that was grasped affected the height of the grasping points, indicating that participants adjusted their grasping behaviour to the slipperiness of the surface. However, the tendency to grasp closer to the rough area was minimal. This shows that the judged COM largely determines how an object is grasped. Friction has very limited influence.

Keywords Grasping · Centre of mass · Object roughness · Grasp point selection

✉ Catharina Glowania
catharina.glowania@uni-bielefeld.de

1 Cognitive Neuroscience/Cognitive Interaction Technology Center of Excellence (CITEC), Bielefeld University, Universitätsstraße 25, 33615 Bielefeld, Germany

2 Department of Human Movement Sciences, Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands

3 Department of Biomechanical Engineering, Faculty 3ME, TU Delft, Delft, The Netherlands

4 University of Essex, Wivenhoe Park, Colchester CO4 3SQ, UK

Introduction

Imagine the following situation: while baking, you want to add oil to the dough, but you see that the usual grasping point in the middle of the oil bottle is really fatty and will probably be slippery. What would be the best place to place your fingers? Here we investigated whether people deviate from their preferred grasping point when the object's surface varies in slipperiness.

To obtain a stable grasp, there are usually many possible places at which one could place one's fingers. Even for a precision grip or pinch grasp, which involves only two fingers, the number of possible grasping points is generally huge. However, where people place their digits is usually quite predictable. There are obviously physiological and biomechanical constraints, like the maximal distance between the fingers, some postures and changes in posture being more comfortable than others, and some movements being more energy efficient (e.g. Zelik and Kuo 2012; Rosenbaum et al. 1990; Soechting et al. 1995; Paulun et al. 2014). The grip force that participants will need to apply to lift an object can obviously also be an important factor for choosing grasping points (Fu et al. 2010). Generally, positions at opposite sides of the object with respect to the centre of mass (COM) are chosen since grasping there minimizes torques. Grasping in this way is energy efficient and therefore makes maintaining a stable grasp easier. Bingham and Muchisky (1993) showed that humans can accurately judge the location of the COM using object symmetry. Lee-Miller et al. (2016) have shown that an object's COM is judged from its visual appearance and that anticipatory planning of digit forces and placement is done on the basis of this visual estimate of the COM. Lederman and Wing (2003) showed that subjects actually grasp in such a way that the grasp axis (axis between the thumb and index finger) passes near or through the COM (also see Kleinholdermann et al. 2007; Goodale et al. 1994; Wing and Lederman 1998; Endo et al. 2011). Especially for heavy objects, it is important to grasp as close to the COM as possible, because in that case small offsets can lead to substantial torques (Paulun et al. 2014, 2016). However, there seems to be a bias toward the acting hand, leading to a more rightward shifted grasp if the right hand is used and a leftward shifted grasp if the left hand is used (Paulun et al. 2014).

In the above-mentioned baking example, however, the area around the COM is slippery (it has a low friction coefficient), so it might not be the optimal place to grasp the object because the object might slip. The additional grip force that is needed to prevent the object from slipping also results in a more energy-consuming grasp (Edin et al. 1992; Cole et al. 1999; Hiramatsu et al. 2015). In a study that included a condition that was very similar to the slippery oil bottle, Paulun et al. (2016) presented participants with cylinders made of different materials (styrofoam, wood, brass and brass covered in Vaseline) in different orientations. The participants had to grasp the cylinders and put them in a goal area. When analysing the grasping kinematics, they found that the grasp points varied more for cylinders with a high friction coefficient than for cylinders with a low friction coefficient, indicating less careful placing of the digits when the friction coefficient was high. They also found that participants grasped closer to the COM for objects with lower friction coefficients (e.g. slippery brass) than for objects with higher friction coefficients (e.g. brass). Furthermore, besides different friction coefficients, the different cylinders also had different weights. Paulun and colleagues showed that for heavier objects (e.g. brass compared to styrofoam) participants grasped nearer to the COM to avoid torques. In a study by Wing and Lederman (2009), participants were asked to lift and place a bar with smooth and rough grips located left and right of the centre. When grasping the bar with a pinch grasp, the participants preferred the rough grip to the smooth one. Only when the rough grip was further away from the centre than the smooth one, resulting in higher torque, was the smooth grip preferred. The grips limited the choice of grasp point selection, since participants could only choose between two positions. Here, we investigated how a surface's friction coefficient influences grasping behaviour when grasping points are not pre-defined.

In summary, object properties like weight, roughness and the location of the COM all contribute to the selection of grasping points. In the present study, we brought two of the above-mentioned properties in conflict: placing one's fingers near the COM and placing them on a surface with a high friction coefficient. We presented participants with polished aluminium bars of two different lengths, and therefore two different weights. They had to pick these up using a pinch grip and place them back on a table. The bars had high friction coefficient areas that were covered in anti-slip tape and low friction coefficient areas of polished aluminium. We expected participants to grasp toward the rough side of the object, as the results of Wing and Lederman (2009) would suggest. Furthermore, as baseline conditions, we presented rough bars that were completely covered in anti-slip tape and smooth bars of which the surface was all of polished aluminium. Based on the work by Paulun et al. (2014, 2016), we expect higher grasping point variability for the rough bars compared to the smooth bars, and also higher variability for the smaller bars because the torque resulting from an off-centre grasp is lower for smaller objects than for larger objects.

Our main question is which grasping points humans choose when the generally preferred grasping point—the object's centre—is smooth, whereas an off-centre area is rough. Will the fact that they can see that the surface is less slippery at one side make them select grasping points that are closer to that side? We furthermore investigated whether the grasping point variability changes with object roughness, as it did in the studies of Paulun et al. (2014, 2016).

Material and methods

Participants

In total, 15 participants (age 23–30, 4 male) took part in this study. All participants self-reported to be right handed. They gave informed consent prior to the start of the experiment. This study was part of a project that was approved by the ethical committee of the faculty of Behavioural and Movement Sciences at Vrije Universiteit Amsterdam.

Stimuli

Two sets of polished aluminium bars were used: large bars with a length of 260 mm, a height and width of 40 mm and a weight of 298 g, and small bars with a length of 130 mm and the same height and weight of 148 g. As a baseline condition, one large bar and one small bar were completely covered in anti-slip tape (Easy Work Antirutsch Antislip Klebeband) to increase the friction coefficient (see Fig. 1a, left side). Completely covered in anti-slip tape, the weight was 320 g for the large bar and 160 g for the small bar. Another large and small bar remained completely smooth, in addition to the baseline conditions there were trade-off conditions (see Fig. 1a, right side). In the trade-off conditions, the border of the area with a high friction coefficient was not always at the centre. In these conditions, the bars varied in the horizontal offset between the centre of the bar and the edge of the high friction coefficient area, with offsets of 0, 1 and 2 cm. In total, ten different bars were used. With the added weight of the anti-slip tape on one side of the bar, the COM was also slightly shifted from the centre of the length of the bar in the direction of the anti-slip tape (by 1.07–1.16 mm for the small bars and 2.27–2.31 mm for the large bars).

Task

Participants were seated in front of a table with their body midline aligned with the centre of the bars. The different bars were presented in a randomized order. The location of the rough area—whether on the right side or the left side of the bar—was also randomized. Each bar was presented ten times, whereby (for the partially covered bars) the rough part of the bar was on the left for half the trials and on the right for the other half. In total, participants performed 100 trials. The participants' task was to move their hand from a starting position 36 cm to the right of the centre of the bar (finger starting position) to the bar, grasp it with a pinch grasp, lift it and put it back down. The participants had 3 s to perform the task. Infrared LEDs were attached to the nails of the thumb and index finger to track their positions. The position and movement of the index fingers and thumbs of the participants were sampled with two Optotrak 3020 (Northern Digital Instruments) infrared tracking cameras at 300 Hz.

Analysis

We determined the grasping points using the multiple sources of information method (MSI method) of Schot et al. (2010). The criteria used for determining the moment of grasping were: the distance between the index finger and thumb markers was smaller than 72 mm (2 mm more than the sum of the bar diameter of 40 mm + 15 mm for the thumb and marker + 15 mm for the index finger and marker) and larger than 62 mm (to exclude the start of the movement when the fingers touched each other), the velocity of the fingers was lower than 0.005 m/s, and the thumb and index finger were at their lowest height after lift-off from the finger starting position. The grasping centre was calculated by taking the mean of the x, y and z-coordinates of the thumb and index finger. We used the difference in position between the grasping centres for trials in which the rough side of the bar was on the right and those for trials in which the rough side of the bar was on the left as our measure of the bias toward the rough surface. Since this difference includes the effect of an off-centre rough side twice (once to the left and once to the right side), we divided this difference between grasping points for right-side and left-side rough surfaces by two to obtain our measure of the bias toward the rough surface area. A bias of zero would mean that the participants ignored the surface roughness altogether. A positive value indicates that the participant grasped closer to the rough side of the bar. We also calculated the mean horizontal and vertical grasp point as well as the individual standard deviation (SD) for each participant in the baseline conditions. We averaged the individual standard deviations to get the mean variability in grasping points.

For the statistical analysis, we used a 2 (sizes) × 2 (cover types) repeated measures ANOVA to test for differences in grasping variability in the baseline conditions and a 2 (sizes) × 3 (offsets) repeated measures ANOVA for the mean grasp point in the trade-off conditions. We used two one-sided t tests (for individual average grasping points for

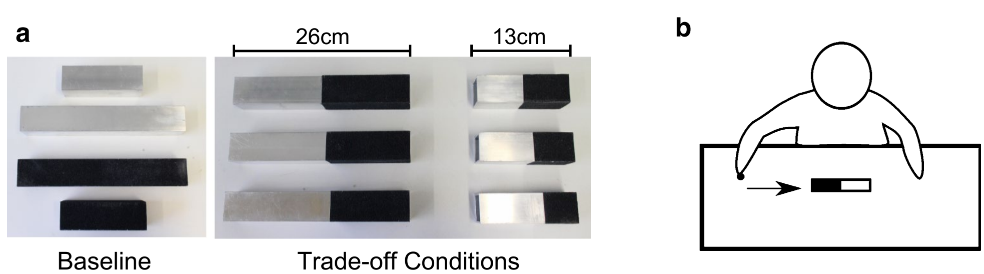
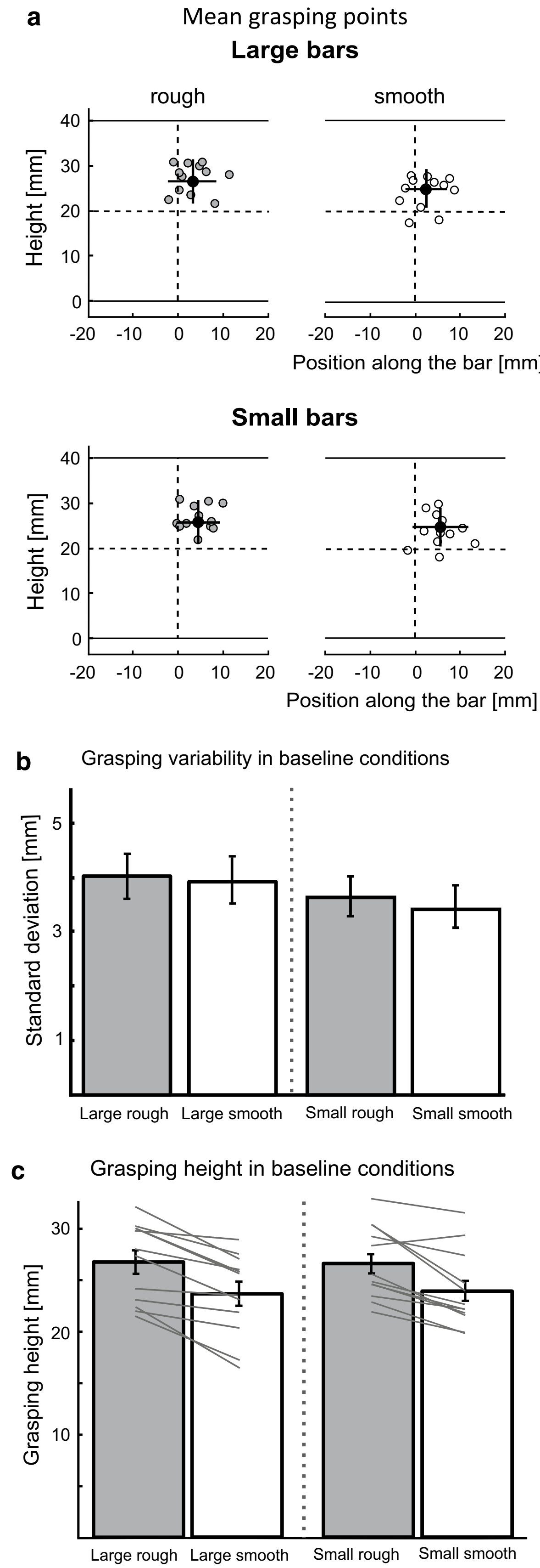


Fig. 1 **a** The stimuli. *Left side* baseline stimuli which were either covered in anti-slip tape or left blank (only polished aluminium). *Right side* trade-off inducing stimuli which were partially covered in anti-slip tape. **b** The setup. The participant was seated in front of a table with the body midline aligned with the middle of the bar. The *dot* marks the starting point. The *arrow* indicates the direction of the grasping movement

Fig. 2 **a** Grasping points for the different bar sizes and surfaces. The ▸ *dashed lines* mark the bars' centres of mass in the vertical and horizontal direction. The *solid lines* are the top and bottom of the bar. The *grey* and *white circles* are the mean grasping points of individual participants for the rough and smooth bars, respectively. The *black dot* marks the mean of all the individual mean grasping points, with a *cross* indicating the standard deviations. The *top plots* show the results for the large bars; the *bottom plots* for the small bars. **b** Grasping point variability in the horizontal direction in the baseline conditions. The *dark bars* show the average of the standard deviations of all participants for the rough baseline bars. The *white bars* show the average for the smooth baseline bars. The *error bars* are the standard errors across participants. **c** Mean grasping heights (*bars*) with standard errors across participants (*error bars*) as well as individual mean grasping heights (*grey lines*) for the different baseline conditions



each bar size, irrespective of the offset) to examine whether there was any tendency to grasp closer to the rough surface at all.

Discarded trials

While grasping and lifting the bar, the participant, for a moment, could accidentally block both cameras and thus create gaps in the movement recording. If those gaps occurred at a moment that interfered with one or more of the above-mentioned criteria for grasp point selection or at the point of grasping, the grasp point detection failed. If that happened, we discarded the trial. If 20% or more of the trials for one participant needed to be removed, we excluded that participant. In total three participants were excluded. The remaining 12 participants had on average 4.3% of all trials removed. The removed trials were evenly distributed across bar sizes and positions of the rough surface (1–4%), except for the large rough bar in the baseline condition. In this condition, 8% of all trials were removed, mainly because for one participant 50% of the trials in this condition needed to be removed. For all other participants, between 0% (eight participants) and 20% (one participant) of the trials in this condition were removed.

Results

Grasp point variability in the baseline conditions

In the baseline condition, we compared grasping point variability for large and small bars that were either rough or smooth. Figure 2a shows the mean grasping points for each participant as well as the grasping points averaged over participants and the corresponding standard deviations. The mean grasping points are close to the centre of the bar, but the previously reported rightward bias (Paulun et al. 2014;

Kleinholdermann et al. 2013) is visible here too. Figure 2b shows the mean horizontal grasping variability. A 2 × 2 repeated measures ANOVA on the grasping point variability with size and roughness as within-subject factors did not show any differences between sizes [large/small: $F(1,11) = 0.73$, $p = 0.4$] or between levels of roughness [smooth/rough, $F(1,11) = 0.25$, $p = 0.6$]. The interaction of size and roughness was not significant [$F(1,11) = 0.05$, $p = 0.8$].

Figure 2c shows the mean grasping heights for the baseline conditions. There is a difference in the grasping height for rough and smooth bars. Participants grasped lower when the bar was smooth than when the bars were covered in anti-slip tape. A repeated measures ANOVA on the grasping height with the factors size and roughness revealed a significant effect of roughness [$F(1,11) = 42$, $p < 0.001$]. There was no effect of size [$F(1,11) = 0.03$, $p = 0.9$] or interaction between size and grasping height [$F(1,11) = 0.66$, $p = 0.4$].

Grasping points in the trade-off conditions

The main question of this study was how humans adjust their grasping behaviour to a trade-off between the centre of mass and an off-centre area with a high friction coefficient. To examine this, participants were asked to lift bars with different offsets of the high friction coefficient area (see Fig. 1a, trade-off conditions). Figure 3 shows the bias toward the rough side of the bar, for the three different offsets of the high friction coefficient area. A 2 × 3 repeated measures ANOVA on the grasping points with "bar size" and "offset" as factors showed no significant main effects [size: $F(1,11) = 4.4$, $p = 0.06$; offset: $F(2,22) = 0.1$, $p = 0.9$], but there was a significant interaction between size and offset [$F(2,22) = 3.9$, $p = 0.03$]. The bias was larger for the small offsets when the bar was large, but larger for the large offset when the bar was small. To test whether there is any effect of roughness at all, we performed two *t* tests comparing the mean bias with zero for the large and small bars. These *t* tests showed a significant bias for the large bars [$t(11) = 2.4$, $p = 0.03$] and no significant bias for the small bars [$t(11) = 0.5$, $p = 0.6$].

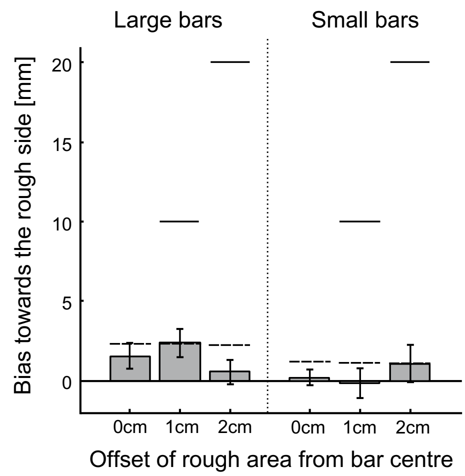


Fig. 3 Influence of the rough surface for each bar size. The *left side* shows data for the large bars and the *right side* data for the small bars. The *y-axis* shows the bias toward the rough side of the bar in millimetres (with respect to the midpoint of the bar). A positive bias means that the participants grasped closer to the rough side of the bar. The *x-axis* shows the offset of the rough area from the midpoint of the bar. The *error bars* indicate the standard error across participants. The *dashed horizontal lines* indicate the positions of the centre of mass, which was shifted slightly from the midpoint of the bar due to the rough tape. The *solid horizontal lines* indicate the positions of the edge of the rough surface (when it does not coincide with the midpoint)

Discussion

The goal of our study was to investigate how differences in object roughness affect grasp point selection when lifting objects. As baseline conditions, we had small and large aluminium bars that were either completely covered in anti-slip tape to increase roughness or were polished aluminium bars that were much smoother and therefore far more slippery than the rough bars. We expected grasp point variability to be larger for the rough bars than the smooth bars, because for objects with a larger friction coefficient the cost of grasping off-centre is smaller than for slippery objects. However, grasp point variability did not depend on the size or roughness of the object. In a previous study, grasp point variability was higher for objects that were both lighter and rougher (Paulun et al. 2014). One explanation for the difference between the results is that our bars were much heavier (small: 148 g, large: 298 g) than the bars that Paulun et al. used in their study (42.3 and 0.8 g). For heavier bars, the cost of an off-centre grasp is larger due to the higher torques it would result in. Another explanation could be that the weight difference between the two bar weights (small vs. large) was too small in our study. In the study of Paulun et al., the heavier bar was about 53 times the weight of the lighter bar, whereas in our study the heavier bar was only twice the weight of the lighter bar. Even in the study by Paulun et al. (2014), the grasp point did not vary very much, even for the very light rough object, suggesting that the centre of the objects is a preferred grasp point even if grasping off centre would not mean having to counteract much extra torque.

We observed that participants grasped significantly lower in the baseline conditions in which the bars were smooth. Paulun et al. (2016) also observed lower grasping points for more slippery objects. They argue that grasping lower might reflect a safety strategy. A lower grasp gives one more time to adjust the grasping force if the object starts to slip during the lift. Furthermore, placing the finger further from the top of the object might result in one using a larger part of the finger (more skin) to grasp the object, which will increase the friction. There are therefore good reasons to grasp smoother objects lower than objects with a higher friction coefficient. The differences between the vertical grasping points that we found in the current study indicate that participants did adjust their grasping behaviour to the slipperiness of the surface.

To test whether and how the grasping behaviour changes when a trade-off between the centre of the bar and the friction coefficient is induced, we presented bars with variations in the position of the edge of a high friction coefficient side. We expected participants to grasp off-centre toward the area with the high friction coefficient (solid lines in Fig. 3). Our results show that the grasping point is not influenced much, and not consistently, by an off-centre high friction coefficient area. The participants—on average—did not place their fingers completely on the rough part, as we initially expected. They did appear to sometimes have a modest bias toward the rough area, but we cannot attribute this to the high friction coefficient, because although the effect was significant for the large bar, it is not even bigger than the actual shift of the centre of mass due to the added tape (dashed lines in Fig. 3). Thus, any effect that is present could be due to realizing that the centre of mass has shifted rather than to the friction. Finding an effect for the 1 cm offset condition of the 26 cm bar could be caused by participants having misjudged the position of the edge of the rough surface to be the centre of the object because in this case the offset was less than 7.5% of the length of the bar, which is probably not enough to be conspicuously off-centre considering measured thresholds in a line bisection task (Olk et al. 2004).

Nevertheless, we cannot be sure that friction was not considered at all in the selection of the horizontal grasping points. The pattern of results for the large bar is not unreasonable in terms of aiming to increase friction. Keeping in mind that we use the middle of the fingernail as our reference, and the grasping area is larger than just this one point, the thumb and index finger do touch the rough part when the centre of the digit is still some distance away. Thus, when the offset is at the centre, it may make sense to shift the grip slightly to make contact with the rough surface with a larger part of the digit's surface, and when the border is not too far away it makes sense to try to touch the high friction coefficient to some extent while also minimizing the torque. According to Peters et al. (2009), the average fingertip area is approximately 350 mm^2 for females and approximately 420 mm^2 for males. Assuming that the touching area is more or less elliptical, with double the length of its width that would mean that the short side of the grasping area has a radius of about 7.5 mm for females and 8.2 mm for males. A bias of 2 mm would therefore be just enough to slightly touch the rough area in the 1 cm offset condition. However, since participants also have other biases, they might sometimes shift more than 2 mm and sometimes not shift at all, thereby making enough contact for it to be useful. When the border is further away there is no point shifting slightly, so better not shift at all. However, despite these possibilities, the fact that there is clearly no attempt to grasp the rough side of the smaller bars makes us reluctant to conclude that the friction had any systematic effect.

Though we did not find strong effects of object texture on grasping behaviour in this study, we cannot generally exclude that there might be an influence of object texture in more extreme cases. Future research could for instance address whether an influence of object texture can be observed in cases such as the slippery oil bottle from the introduction or objects partially covered in Vaseline. However, it is important to note that in such cases, the oil or Vaseline will also stick to the participants' fingers and participants might not want to grasp the oily part for reasons other than slipperiness per se. It is also for this reason that we chose to use actual surface textures rather than manipulate slipperiness using coatings of varying viscosity. Our results suggest that participants are reluctant to grasp off-centre, irrespective of any differences in the friction coefficient along the object, which is in line with previous research (Paulun et al. 2014, 2016). When the participants in the Paulun studies grasped very light non-slippery objects, they grasped close to the centre, although the torque that would arise from grasping far off-centre would be very small. Thus, our findings are consistent with previous studies by Paulun et al. (2014), Goodale et al. (1994) and Lederman and Wing (2003) that report a strong preference for grasping near the centre of an object. We found that instead of grasping off-centre by an area with a high friction coefficient, participants try to compensate for the low friction in the centre by grasping lower.

Acknowledgements CG was supported by a grant from IEEE's Technical Committee on Haptics (Student Exchange Program for Cross-Disciplinary Fertilization) and the Cluster of Excellence Cognitive Interaction Technology 'CITEC'(EXC 277) at Bielefeld University, which is funded by the German Research Foundation (DFG). MAP was supported by a VENI Grant (MaGW 451-12-040) from the Dutch organization for scientific research (NWO).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964

Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

References

Bingham GP, Muchisky MM (1993) Center of mass perception and internal frames of reference. Percept Psychophys 54(5):617–632

Cole KJ, Rotella DL, Harper JG (1999) Mechanisms of age-related changes of fingertip forces during precision gripping and lifting in adults. J Neurosci 19(8):3238–3327

Edin BB, Westling G, Johansson RS (1992) Independent control of human finger-tip forces at individual digits during precision lifting. J Physiol 450:547–564

Endo S, Wing AM, Bracewell RM (2011) Haptic and visual influences on grasp point selection. J Mot Behav 43(6):427–431. doi:10.1080/00222895.2011.621996

Fu Q, Zhang W, Santello M (2010) Anticipatory planning and control of grasp positions and forces for dexterous two-digit manipulation. J Neurosci 30(27):9117–9126

Goodale MA, Meenan JP, Bülthoff HH, Nicolle DA, Murphy KJ, Racicot CI (1994) Separate neural pathways for the visual analysis of object shape in perception and prehension. Curr Biol 4:604–610

Hiramatsu Y, Kimura D, Kadota K, Ito T, Kinoshita H (2015) Control of precision grip force in lifting and holding of low-mass objects. PLoS ONE 10(9):e0138506. doi:10.1371/journal.pone.0138506

Kleinholdermann U, Brenner E, Franz VH, Smeets JBJ (2007) Grasping trapezoidal objects. Exp Brain Res 180:415–420

Kleinholdermann U, Franz VH, Gegenfurtner KR (2013) Human grasp point selection. J Vis 13(8):23, 1–12. doi:10.1167/13.8.23

Lederman SJ, Wing AM (2003) Perceptual judgment, grasp point selection and object symmetry. Exp Brain Res 152:156–165

Lee-Miller T, Marneweck M, Santello M, Gordon AM (2016) Visual cues of object properties differentially affect anticipatory planning of digit forces and placement. PLoS ONE 11(4):e0154033. doi:10.1371/journal.pone.0154033

Olk B, Wee J, Kingstone A (2004) The effect of hemispatial neglect on the perception of centre. Brain Cogn 55:365–367

Paulun VC, Kleinholdermann U, Gegenfurtner KR, Smeets JBJ, Brenner E (2014) Center or side: biases in selecting grasp points on small bars. Exp Brain Res 232:2061–2072

Paulun VC, Gegenfurtner KR, Goodale MA, Fleming RW (2016) Effects of material properties and object orientation on precision grip kinematics. Exp Brain Res 234:2253–2265. doi:10.1007/s00221-016-4631-7

Peters RM, Hackeman E, Goldreich D (2009) Diminutive digits discern delicate details: fingertip size and the sex difference in tactile spatial acuity. J Neurosci 29(50):15756–15761

Rosenbaum DA, Marchak F, Barnes HJ, Vaughan J, Slotta JD, Jorgensen MJ (1990) Constraints for action selection: overhand versus underhand grips. In: Jeannerod M (ed) Attention and performance XIII: motor representation and control. Erlbaum, Hillsdale, pp 321–342

Schot WD, Brenner E, Smeets JBJ (2010) Robust movement segmentation by combining multiple sources of information. J Neurosci Methods 187:147–155

Soechting JF, Buneo CA, Herrmann U, Flanders M (1995) Moving effortlessly in three dimensions: does Donders' law apply to arm movement? J Neurosci 15(9):6271–6280

Wing AM, Lederman SJ (1998) Anticipating load torques produced by voluntary movements. J Exp Psychol Hum Percept Perform 24(6):1571–1581

Wing AM, Lederman SJ (2009) Points for precision grip. In: Nowak DA, Hermsdörfer J (eds) Sensorimotor control for grasping: physiology and pathophysiology. Cambridge University Press, Cambridge, pp 193–203

Zelik KE, Kuo AD (2012) Mechanical work as an indirect measure of subjective costs influencing human movement. PLoS ONE 7(2):331143. doi:10.1371/journal.pone.0031143