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Title:

Grip force and force sharing in two different manipulation tasks with bottles

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Abstract

Grip force and force sharing during two activities of daily living were analysed experimentally in ten right-handed subjects. Four different bottles, filled to two different levels, were manipulated for two tasks: transporting and pouring. Each test subject's hand was instrumented with eight thin wearable force sensors. The grip force and force sharing were significantly different for each bottle model. Increasing the filling level resulted in an increase in grip force, but the ratio of grip force to load force was higher for lighter loads. The task influenced the force sharing but not the mean grip force. The contributions of the thumb and ring finger were higher in the pouring task, whereas the contributions of the palm and the index finger were higher in the transport task. Mean force sharing among fingers was 30% for index, 29% for middle, 22% for ring and 19% for little finger.

Keywords:

Grasping, grip force, force sharing

Practitioner Summary

We analysed grip force and force sharing in two manipulation tasks with bottles: transporting and pouring. The objective was to understand the effects of the bottle features, filling level and task on the contribution of different areas of the hand to the grip force. Force sharing was different for each task and the bottles features affected to both grip force and force sharing.

1. Introduction

The human hand is one of the most complex biomechanical systems in the world. To date, its versatility in grasping and manipulating objects has not been matched by any artificial device. Muscle activation during grasping tasks allows hand shaping while reaching to grasp and facilitates the distribution of contact forces with the object during manipulation. Successful manipulation is accomplished through complex control of muscle activation, which is carried out by the central nervous system (CNS) and facilitated by visual and tactile sensory signals from the afferent neural system. Grasping with prosthetic hands still cannot replicate this level of dexterity, even with modern myoelectric devices (Micera *et al.* 2010). Thus, knowledge of the force distribution in the natural hand while grasping is important not only to improve the control and mechanical design of prosthetic hands but also for product design and for evaluating hand function (Kargov *et al.* 2004).

Although several studies have measured the grasping forces exerted by the hand, most of them have focused on pinch prehension or have used specific instrumented devices rather than real objects (Aoki *et al.*, 2006; Kinoshita *et al.,* 1995; Radwin *et al.*, 1992; Reilmann *et al.* 2001; Santello and Soechting 2000, Kong *et al.*, 2011, Kuo *et al.*, 2013). The grip force and the relative contributions of different areas of the hand have also been studied for the design of handles (Lee *et al.*, 2009; McGorry and Lin 2007; Kong *et al.*, 2014). Specific devices have been designed for studying the grip force distribution, especially for cylindrical handles (Chadwick and Nicol, 2001; Dong *et al.*, 2008; Rossi *et al.*, 2012) and recently for pliers (Kim *et al.*, 2016). Most of the studies analysing the contributions of different hand areas to the grip force have used cylindrical objects because they can easily be wrapped with thin pressure sensors, such as the Tekscan or Fuji Film pressure mapping systems (Nicholas *et al.*, 2012; Pataky *et al.*, 2012, Wu *et al.*, 2014). While other studies have used functional objects, such as bottles, only kinematics and hand shaping have been analysed (Ansuini *et al.*, 2008; Crajé *et al.*, 2011; Sartori *et al.*, 2011) but not the forces applied. Similarly some recent studies analysed multi-finger grasping postures with cylindrical objects of different diameters, which can be assimilated to some functional objects such as bottles, but without registering the forces performed (Lee & Jung, 2015, Jarque *et al.*, 2016). A recent study used specially designed instrumented objects to simulate functional objects used in pouring tasks, but only a three-digit grip was analysed (Manis and Santos, 2015). Moreover, the fact that the sensors had specific locations on the instrumented objects may have prevented the spontaneous selection of the grasp by the subjects. Attention has been drawn to the lack of research on grip-force distribution in the hand during functional whole-hand grasping (Pylatiuk *et al.*, 2006) and can be partially explained by the difficulty of finding suitable and non-invasive sensors. Pylatiuk *et al.* (2006) analysed functional manipulation of bottles using specially designed discrete force sensors placed on the hand, which were 9 mm in diameter and 3 mm thick. In a recent study, Hermsdörfer *et al.* (2011) analysed forces during the manipulation of several objects associated with routine activities of daily living, but they only measured contact forces on the fingertips of three grasping fingers.

The problem of motor redundancy owing to multi-finger force production has been highlighted in previous studies (Zatsiorsky *et al.,* 1998, Kolossiatis *et al.,* 2016); the same total grip force can be obtained with different contributions of the individual fingers, which is referred to as force sharing. However, force sharing in functional tasks related to activities of daily living (ADL) has not been sufficiently studied. (Rossi *et al.*, 2012) showed that force sharing among fingers is affected by the grip size in cylindrical handles during power grip. Force sharing among the fingers has also been reported to be different for a pressing task and for an adapted power grip task (Vigouroux *et al.*, 2011). However little is known about the effect of the object features or the task in the force distribution among the fingers, thumb and palm during functional grasping in ADL tasks.

The aim of the present study was to improve our understanding of the most common grasps used in ADL. The manipulation of bottles and similar objects is a typical ADL and is usually included in protocols for the assessment of grasping ability (Light *et al.*, 2002). Specifically, grip force and grip force distribution in the hand while either transporting a bottle or pouring water from it were analysed. In addition to quantifying the total grip force and the contribution of each area of the hand, the effects of different factors were also studied: the subject, the task being performed, the bottle's features (shape, size) and the amount of liquid in the bottle (filling level). Eight thin, minimally invasive, wearable sensors were used to measure grip force in different areas of the hand.

2. Materials and methods

2.1. Subjects

Ten right-handed subjects (five men and five women), with no history of trauma or pathologies of the upper limb, participated in the experiments after providing informed consent. The mean age was 32.7 years (SD 7.3), the mean hand length 186.7 mm (SD 13.0) and the mean palm hand breadth 82.2 mm (SD 7.1). The protocol used was in compliance with the Declaration of Helsinki and was approved by the ethical committee of the university.

2.2 Objects

Four different bottles were used (Figure 1a): one glass bottle (B1) and three plastic ones (B2, B3, B4). Each bottle was manipulated with two different filling levels (FL1 and FL2), resulting in two different total weights of the bottles (W1 and W2), as shown in Table 1.

2.3. Procedure

The participants were seated on a height-adjustable chair in front of a table so that their elbows were level with the table top. The subjects were asked to perform two different tasks. Task T1 (transport) consisted of taking the bottle from the initial position B on the table (Figure 1b) and moving it anteriorly to leave it at position C, which was 150 mm away from B. Task T2 (pouring) consisted of taking the bottle from the initial position B (Figure 1b), pouring its contents into a cylindrical container (diameter 150 mm, height 150 mm) located at position D (300 mm towards the left of the subject), and returning the empty bottle to position B. At the beginning and end of each trial and task, the subjects' right hand was resting on the table in position A. The subjects were instructed to perform the tasks at a natural speed but were not given any additional instruction about the type of grasp to be used. Each combination of bottle, filling level and task was repeated five times consecutively, preceded by five unrecorded training trials. The bottle order was randomised for each subject. All combinations of filling level and task were performed consecutively for each bottle, with the task and filling level also being randomised for each bottle. All experiments with each subject were performed in the same session.

2.4. Data recording

The subject's hand was instrumented with a wireless system (sample rate 40 Hz) comprising eight thin wearable force sensors (Finger TPS, Pressure Profile Systems, Los Angeles, CA) consisting of capacitive pressure sensor arrays. Figure 1c shows the position of each sensor on the hand: five sensors were located on the distal phalanges of each finger and thumb (DIndex, DMiddle, DRing, DLittle and DThumb), one sensor was on the palm of the hand (Palm) and two additional sensors were on the proximal phalanges of the index and middle fingers (PIndex and PMiddle). At the beginning of the experiment, the subject's right hand was fitted with the sensors. Each sensor was then calibrated according to the procedure recommended by the manufacturer. For the calibration the subject wore the sensors and had to press a load cell once with each sensor, increasing the applied force from zero to a reference force (12 N was used). Both the sensor and the load cell signals were recorded using the software supplied by the manufacturer, which uses this information to establish the relation between the raw signal acquired by the sensor and the pressing force performed. According to the manufacturer, the accuracy error of the system is less than 5% and the repeatability error less than 1%.

The bottles were instrumented with a magnetic tracking sensor (Fastrak Polhemus, Colchester, VT) to record their position during the test. The receiver sensor was attached to the bottle (see contour of sensor position in Figure 1a), and the transmitter was fixed to the table so that the X, Y and Z axes corresponded to medial, anterior and vertical motions, respectively.

2.5. Data analysis

The force and position signals were smoothed with a low-pass filter (zero phase first order filter, forward-backward, 0-20 Hz, using the *filfilt* built-in Matlab function). The data from different trials were synchronised in Matlab by considering the instants with the highest positive and negative derivatives of the Thumb signal as the loading and unloading reference instants, respectively. Time was normalised to the range 0-1 to allow for comparison between different trials, with loading and unloading reference instants set to normalised times 0.3 and 0.7, respectively. The force registered at each of the eight sensors (SF_i, i=1,…,8) was added at each instant to define the grip force (GF). The mean values of the GF and SF_i forces during the time interval 0.4-0.6 were considered as representative of the stable grasp of the bottle being manipulated, defining a mean grip force (MGF) and eight mean sensor forces (MSF_i, i=1,…,8). In order to reduce the effect of the subject on the results, a relative MGF (MGFr) was defined as the ratio between the MGF value for each experiment of a subject and his/her maximal MGF across all his/her experiments. The contribution of each sensor to the grip force (CGF_i, i=1,…,8) was computed at each instant as the quotient between SF_i and GF, and a mean value was obtained during the time interval 0.4-0.6. Force sharing among index, middle, ring and little fingers (FS_j, j=I,M,R,L) was computed for each finger (FS_j, j=I,M,R,L) as the relative contribution of each finger (sum of CGF of the sensors in that finger) to the sum of the CGF of the sensors located in the four fingers, as in other works in the literature (Li *et al*., 1998; Vigouroux *et al.*, 2011).

2.6. Statistical analysis

The repeatability of the measurements among the five trials was assessed from the root-mean-squared error (RMSE) in an ANOVA on MSF with factor 'subject x bottle x task x filling level x sensor'. As the repeatability was good, the mean value of the five trials was used for each experiment in the subsequent statistical analysis.

The effect of the different factors on the total grip force was investigated by performing an ANOVA on MGFr with factors 'bottle', 'task' and 'filling level' and their interactions. As B1 bottle had different tare weight than B2, B3, B4 bottles and also total weights for each filling level were different for both groups (Table 1), two additional ANOVAs were performed on MGFr in order to have a deeper understanding on the effect of each factor and their interaction with others: one including only the experiments with the glass bottle and the other one with the three plastic bottles. The relative contributions of each area of the hand to the grip force were analysed using similar independent ANOVAs on the CGF of each sensor, with the same independent factors. Also force sharing among fingers was compared for the two tasks. Post-hoc Tukey-Kramer analyses were performed on the ANOVA results to determine possible groupings among the different levels of the variable 'bottle' and to compute marginal means. The effect of the subject gender on the results was also investigated with new ANOVAs extended by adding the factor 'gender' and also the interaction of this new factor with the other factors. The Matlab Statistics Toolbox was used for these analyses, with a significance level of 0.05 in all the analyses.

3. Results

Figure 2 shows typical bottle displacements during the two tasks. For the transport task T1, the Y-position showed a smooth transition from the initial to the final state, the Z-position followed a bell-shaped curve, and the X-position remained constant. For the pouring task T2, the Z-position followed an eccentric bell-shape because of the slower velocity in the ascent than in the descent of the bottle, the X-position showed an S-shaped profile due to the rotation of the bottle for pouring the water, while the Y-position was quite constant. The eccentricity of the Z-position curve was found to increase with the filling level of the bottle. The mean time spent on T1 from loading to unloading instants (corresponding to normalised times 0.3 and 0.7 respectively) was 1.08 s (SD 0.21) for filling level FL1 and 1.22 s (SD 0.24) for filling level FL2, and 4.75 s (SD 1.39) and 8.47 s (SD 2.17) on T2, respectively.

The temporal evolution of the normalised GF by task, averaged across all trials for each task, is shown in Figure 3, where normalisation was performed by setting the maximum GF in any trial to 100. A common pattern was observed in both tasks, with three different phases: a sudden increase in GF during the loading phase, followed by a decrease in GF during the manipulation (more pronounced for the T2 task), and a final decrease in GF during the unloading phase. A change in the GF rate during T2 was observed at the moment of highest inclination of the bottle, which was at the end of the pouring task (around normalised time 0.6). This change was more noticeable for the heaviest bottle (B1).

The repeatability error associated with the five different repetitions of each combination of factors, obtained from the RMSE of the ANOVA on MSF with the factor 'subject x bottle x task x filling level x sensor', was 0.75 N (SD 0.45). Table 2 shows the results of the ANOVA on MGFr with factors 'bottle', 'filling level' and 'task'. The 'bottle' and 'filling level' had a significant effect on MGFr, whereas the effect of the 'task' was not significant. The interaction between 'bottle' and 'task' was also significant. Figure 4 shows the mean MGF for both transport and pouring tasks for each combination of 'bottle' with 'filling level'. The two additional ANOVAs restricted only to bottles of the same material (B1 for glass, and B2,B3,B4 for plastic) showed that none of the factors 'filling level' or 'task' was significant on MGFr for the experiments with the glass bottle, but 'filling level' and also the interaction 'bottle x task' had a significant effect on MGFr in the case of the plastic bottles. The effect of the gender of the subject was not significant on MGF or MGFr, nor the interaction of this factor with other factors such as the bottle, the task of the filling level.

The post-hoc Tukey-Kramer analysis on the factor 'bottle' revealed that the bottle B1 was manipulated with a significantly greater MGFr than the three plastic bottles (B2, B3 and B4), and that the difference among these three plastic bottles was not significant. This was confirmed also for MGF. Mean MGF across all the experiments for each bottle was 28.1 N (B1), 15.5 N (B2), 14.9 N (B3) and 14.1 N (B4). The post-hoc analysis on the factor 'filling level' with all the bottles showed that MGF was greater for FL2 (20.6 N) than for FL1 (15.7 N), as expected from the differences in weight arising from the different filling levels. The same analysis but restricted only to the plastic bottles showed also significant differences for FL2 (17.8 N) and FL1 (11.9 N), although the relative increase in MGF with the greatest filling level was smaller than the increase in the total weight (from 150 g to 550 g). Additionally, the filling level did not produce a significant change in the MGF for the glass bottle (28.8 N for FL2 and 27.3 N for FL1) despite the total weight for FL2 was nearly twice that for FL1. Lastly, the glass bottle with filling level FL1 was manipulated with a greater MGF (27.3 N) than the plastic bottles with FL2 (18.6 N for B2, 17.8 N for B3, 16.9 N for B4), despite the total weight being manipulated was the same. The post-hoc analysis on the interaction 'bottle x task' restricted to the plastic bottles revealed that executing the pouring task T2 with bottle B2 required a greater MGF (18.2 N) than the rest of bottle-task combinations (ranging from 12.8 N to 15.2 N).

Figure 5a represents the mean values of CGF for each sensor across all the subjects and experiments. The marginal means for each bottle, filling level and task are represented with symbols around the overall mean value. The statistical significance of the factors obtained from the ANOVAs on each sensor is indicated in Fig. 5a with an asterisk. The DThumb sensor (1) had the highest contribution to the GF and the lowest CGF was that of the PMiddle (8) sensor. The factor 'bottle' had significant effects on the CGF for most of the sensors, including the DThumb (1), DIndex (2) and DMiddle (3) sensors. Bottle B2 behaved with a noticeable different pattern than that of the other bottles, with a higher contribution of the thumb, palm and ring finger, and a lower contribution of the index finger. The 'filling level' did not affect significantly to the CGF and the 'task' only affected significantly to the CGF of the DIndex (2) sensor, although the results were nearly significant for the DThumb (1) and Palm (6) sensors ($p=0.06$). Similarly, Fig. 5b shows the FS among the fingers and the marginal means for each factor and level. The mean FS was 30.0% for the index, 29.0% for the middle, 22.4% for the ring and 18.7% for the little finger. The 'bottle' and 'task' affected significantly the FS pattern whereas the 'filling level' did not.

4. Discussion

The present study contributes to a better understanding of the differences in the manipulation of bottles by humans depending on the bottle features, the filling level or the task performed. Particularly, we investigated the effects observed in the grip force and the contribution of the different hand areas to the grip force during the manipulation of actual bottles with different designs. This study complements some previous studies analysing the fingers placement and the grasping postures in bottles for different tasks and with different shapes (Ansuini *et al.*, 2008; Crajé *et al.*, 2011; Sartori *et al.*, 2011) and also other recent kinematic studies about grasping cylindrical objects (Lee & Jung, 2015, Jarque *et al.*, 2016). Moreover this study provides additional results about the contribution of the hand areas to the rotation of objects, analysed by Mani & Santos (2015) for three-digit pouring tasks.

The time course of the total grip force during the transport task (Figure 3) was similar to that obtained by others for two-finger lifts and five-finger lifts (Johansson and Westling 1984; Santello and Soechting 2000). The grip force required to transport the bottle is set by the CNS during the very short period of motion onset and is reduced after the acceleration period of the vertical motion for efficiency. During the pouring task, this reduction was more pronounced than for the transport task, which can be attributed to the reduction of weight of the bottle during pouring. Moreover, the reduction was greater after the moment of highest inclination of the bottle, when less precision is demanded because the act of pouring has been completed.

The ANOVA on the MGFr (Table 2) showed that the bottle features and weight had significant effect on the grip force. A higher filling level resulted in an increase in the grip force, as expected, thereby explaining why the interaction of bottle with filling level was not significant in the ANOVA. However, the grip-force to bottle-weight ratio was noticeably higher for lighter bottles (Figure 4 and Table 1), with heavy bottles being manipulated with lower safety factors, which is in agreement with previous reports (Johansson and Westling 1984). This result may explain the fact that the grip force was not altered significantly when changing the filling level for the glass bottle, whereas the change was significant for the plastic bottles, with lower tare weight. One possible explanation for this result is that subjects tend to manipulate heavier (or apparently heavier) objects with a lower safety margin to reduce muscular fatigue. Alternatively, subjects may use higher forces than required on very light objects to prevent slip, thus improving sensory feedback. The effect of inertial and gravitational parts of the load force on grip force adjustment in dynamical tasks has been highlighted previously (Zatsiorsky *et al.*, 2005) and sensory feedback is presented as a possible factor to explain this adjustment. The material of the bottle also seems to play a role in the grip-force to load-force ratio, as the glass bottle was manipulated with a higher MGF than similarly weighted plastic bottles. The different friction coefficient may be a reason for this difference. The lower stiffness of the plastic bottles compared to the glass one may also prevent the subject from developing higher grip forces, which would result in significant deformation of the bottle. Additionally, previous studies have shown that grip force depends on the size and material of the bottle and is higher if the bottle seems heavier than the one in a previous task (Buckingham *et al.*, 2009; Cole, 2008; Li *et al.*, 2009). Domalain et al. (2008) reported, for grips with the thumb and the index finger, an increase in grip force with object width, for objects of the same weight. We cannot confirm this behaviour from our results, despite the task, the grip type and the weight range is different in our work. The bottle features also had a significant effect on the contributions of the different hand areas to the grip force (Fig. 5), probably because the different size and geometry may require different contact configurations between the hand and the bottle, as well as the need to use different force sharing strategies to improve bottle stability. This effect of object shape on grip force distribution has also been observed recently in power grip tasks (Rossi *et al.*, 2015). For the bottle with highest diameter in our experiments (B2), force sharing among fingers was noticeably different than that for the other bottles, with higher sharing for the ring and little fingers and lower for the index and middle fingers (Fig. 5b). Also the palm and thumb were more demanded for B2 (Fig. 5a). These differences are attributed to the bigger size of the bottle, demanding a greater participation of the ring and little fingers while pouring for helping in the stabilisation. It is remarkable that the contribution of the hand areas to the grip force was not dependent on the filling level, indicating that an increase in the filling level can be compensated by a modulation of the grip force, without requiring adjustments of the force sharing. The effect of object size on grip force distribution has been investigated previously for maximal isometric tasks with cylindrical handles (Kong et al., 2007; Rossi *et al.*, 2012) although grip spans were smaller to those used in the present study, limiting the comparison of the results.

Our results show that the bottles were handled with similar total grip forces, regardless of whether transporting or pouring was performed (Table 2), but the contribution of the different hand areas to this grip force was slightly changed for the two tasks being significant the change of the index contribution (Fig. 5) which is higher for the transport task than for the pouring task. This can be explained because in the pouring task the middle, ring and little fingers have a more important role for controlling the inclination of the bottle, reducing the relative contribution of the index among fingers. The effect of the task in the contribution of the thumb and palm was near statistical significance ($p=0.06$), with higher thumb and lower palm contributions for the pouring task. This can be due to the lowered thumb position on the bottle when pouring; in contrast to the other digits, which are located on the upper part of the bottle, and the palm, which is lateral, the thumb must increase its contribution to counteract the gravitational force. Pylatiuk *et al.* (2006) reported similar results when comparing a lifting task with a simulated pouring action using different force sensors to those used in this study. Previous works analysing dynamical tasks have shown that force sharing is affected by the wrist flexion and the external moment to counteract (Dumont *et al.*, 2006). In our study the pouring task required a wrist partially flexed and the transport task a neutral or slightly extended wrist. This fact and the different external moment demanded for each task can explain partially the differences observed in force sharing. The fact that force sharing was partially altered by the task is consistent with the changes observed in previous works in the digit placement or hand configuration for different tasks (Ansuini *et al.*, 2008; Crajé *et al.*, 2011; Sartori *et al.*, 2011), suggesting that this change in the hand configuration could be imposed by the different force-equilibrium requirements imposed by the task.

The analysis of the interaction of the factors ‘bottle’ and ‘task’ for plastic bottles revealed that bottle B2 required a significantly greater MGF for pouring than the rest of the task-bottle combinations. This fact is probably due to the low stiffness of the bottle walls provided by the low wall-thickness to size ratio, which makes more difficult for the subjects maintaining the bottle equilibrium while pouring, thus requiring higher forces to improve the stability. This fact has an implication in the design of bottles because an inadequate size to wall-thickness ratio of the bottle could difficult the manipulation, especially for people with reduced grasping capabilities.

The greatest mean contribution to the total grip force across all the experiments corresponded to the thumb sensor, similarly to other studies (Olafsdottir *et al.*, 2005; Pylatiuk *et al.*, 2006), which is explained by the opposing role of the thumb. From our results, the total contribution of the index finger was similar to that of the middle finger, whereas the ring, little and palm areas made lower contributions, which was also in agreement with another study that used similar objects and tasks (Pylatiuk *et al.*, 2006). The mean force sharing among fingers obtained in this study (index 30.0%, middle 29.0%, ring 22.4% and little finger 18.7%) is similar to those obtained in previous studies for cylindrical grasping (Amis, 1987; Radhakrishnan and Nagaravindra, 1993) and also similar to the results obtained by other studies in pressing tasks (Danion *et al.*, 2001; Vigouroux *et al.*, 2011), indicating that force sharing for real life activities with bottles is similar to that observed in other hand activities. The mean force sharing obtained here for the little finger is higher and that of the index finger lower to those obtained by Rossi et al. (2012). However, it must be considered that the maximum diameter in that study was 48 mm (smaller than that of the bottles in our study) and that they observed an increment in the little force sharing and a decrement in the index force sharing for the highest diameter of 48 mm with respect to smaller diameters.

Despite the contribution of the present study to a better understanding of grip-force sharing during two common ADL, some limitations must be considered. The measurement system used in the present work, Finger TPS, only registered normal forces and is limited to certain areas of the hand, although this is in line with the state of the art in commercial tactile sensors for ergonomic investigations (Reinvee & Jansen, 2014). The repeatability error obtained for the sensors (mean 0.75 N, SD 0.45) confirmed the suitability of the sensors for these types of measurements and indicated that subjects maintained very similar MGF and CGF for consecutive repeated tasks with the same conditions. Other areas of the hand outside the location of the sensors may have contributed to the total grip force but were not considered. Nevertheless, the eight sensors used in the present study covered the main areas used when grasping the bottles employed in this work. Some previous studies registering pressures in the whole hand-handle interface confirm the validity of the sensors location used in the present one, as they have shown that the fingertips are mainly responsible for the gripping forces whereas the proximal phalanges and the palm contributed more in push tasks requiring higher forces (Aldien *et al.* , 2005, Rossi *et al.* 2012) and that among proximal phalanges the highest contribution to the grip force corresponds to the index finger (Goislard de Monsabert *et al.* 2012). The calibration of the sensors could have affected the comparisons between subjects, as the sensor locations for each subject may have been slightly different due to different hand anthropometry. Moreover, changes in the afferent feedback as a consequence of the sensors could have affected the forces exerted on the objects. These limitations have been partially avoided defining a relative MGF (MGFr) for the analysis of the statistical significance of the factors involved in the study. Our investigation was limited to four different bottles with two different filling levels, ranging in weight from 150 and 1000 g, which was considered representative of most of the precision grasps used in daily activities. Only two tasks were analysed, transport and pouring, and the grasping posture was selected freely by the user. Other tasks in ADL may require grasp types that were not analysed in this study, and this should be taken into account when attempting to extend the conclusions to other activities.

Overall, the present work allows to conclude that grip force and force sharing in the manipulation of bottles are significantly influenced by the bottle features. The filling level is also determinant for the grip force, but the ratio of grip force to load force has been shown to be higher for lighter loads. The task to be performed with the bottle influenced the force sharing but not the mean grip force during the task. Comparing transport and pouring tasks, the contributions of the thumb and the ring finger were higher for pouring, whereas the contributions of the palm and the index finger were higher for transport. Mean force sharing among fingers across all the experiments was 30% for index, 29% for middle, 22% for ring and 19% for little finger.

5. Disclosure of potential conflict of interest

The authors declare that no conflict of interest exists.

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Table 1. Characteristics of the bottles: height (h), diameter (d), tare weight (W0) and total weight for both filling levels (W1 for FL1, W2 for FL2).

Bottle	**h (mm)**	**d (mm)**	**Material**	**W0 (g)**	**W1 (g)**	**W2 (g)**
B1	300	80	Glass	523.5	550	1000
B2	350	80	PET	49.0	150	550
B3	245	75	PET	44.5	150	550
B4	222	65	PET	28.5	150	550

Table 2. Results for the ANOVA on MGFr with the factors 'bottle', 'filling level', 'task' and their interactions.

Source	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	**F**	**p-value**
Bottle	3.7956	3	1.2652	54.65	0.000
Filling level	0.8718	1	0.8718	37.65	0.000
Task	0.0197	1	0.0197	0.85	0.357
Bottle x Filling level	0.1224	3	0.0408	1.76	0.157
Bottle x Task	0.2329	3	0.0776	3.35	0.021
Filling level x Task	0.0058	1	0.0058	0.25	0.616
Error	3.4035	147	0.0231		
Total	8.4519	159			

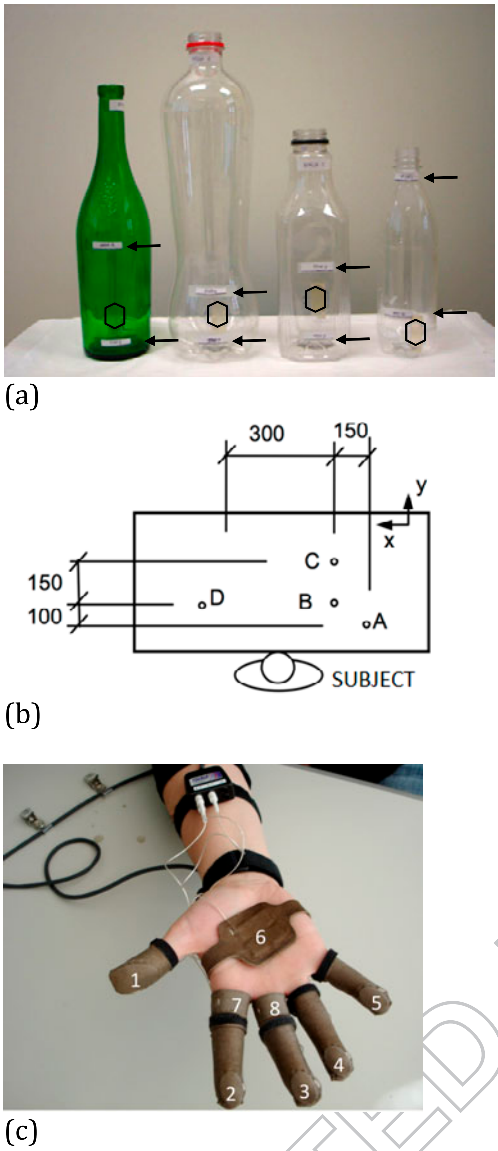


Figure 1. Description of the experimental setup: a) Bottles used in the experiment. From left to right: B1, B2, B3 and B4. Outlines for the placement of the tracking sensors and arrows indicating the two filling levels are shown on each bottle. b) Setup of the table and the subject for the experiments (top view): initial and final positions of the subject's hand (A), initial position of the bottle (B), final position of the bottle for transport task T1 (C), and position of the container to be filled with water during pouring task T2 (D). c) Arrangement of the Finger TPS sensors (Pressure Profile Systems, Los Angeles, CA) on a subject's hand: DThumb (1), DIndex (2), DMiddle (3), DRing (4), DLittle (5), Palm (6), PIndex (7), PMiddle (8).

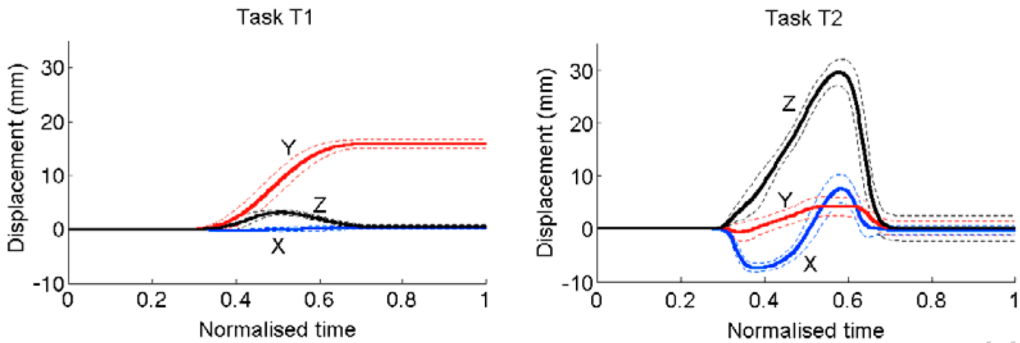


Figure 2. Mean (solid line) and standard deviation (dashed lines) displacements of the bottle sensor for one subject moving bottle B2 with filling level FL1 for both tasks: left, transport task T1; right, pouring task T2.

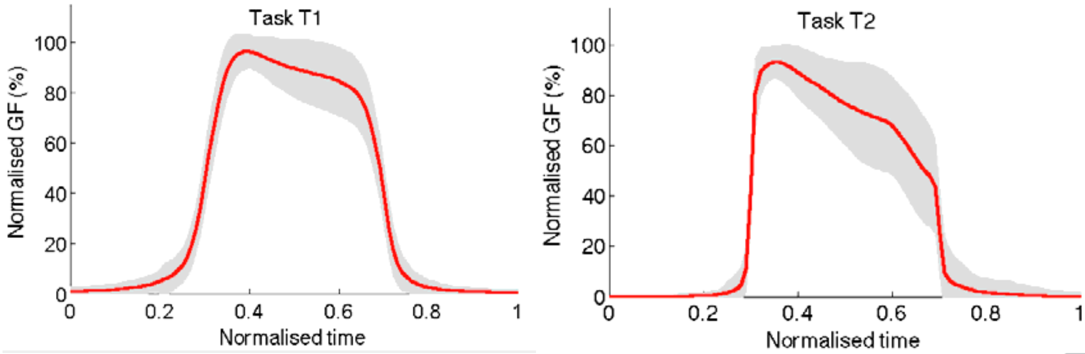


Figure 3. Mean and standard deviation of normalised GF across all the experiments for both tasks: left, transport task T1; right, pouring task T2. Normalisation was performed by setting the maximum GF in any trial to 100.

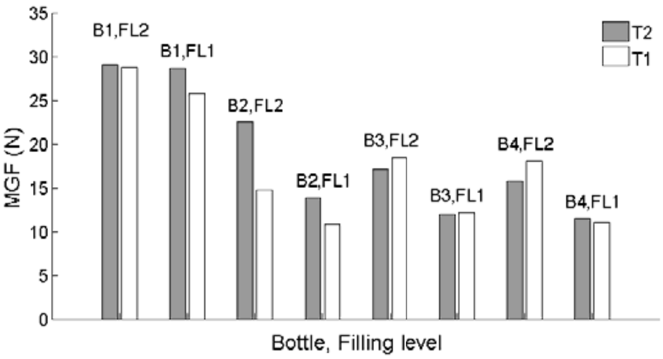
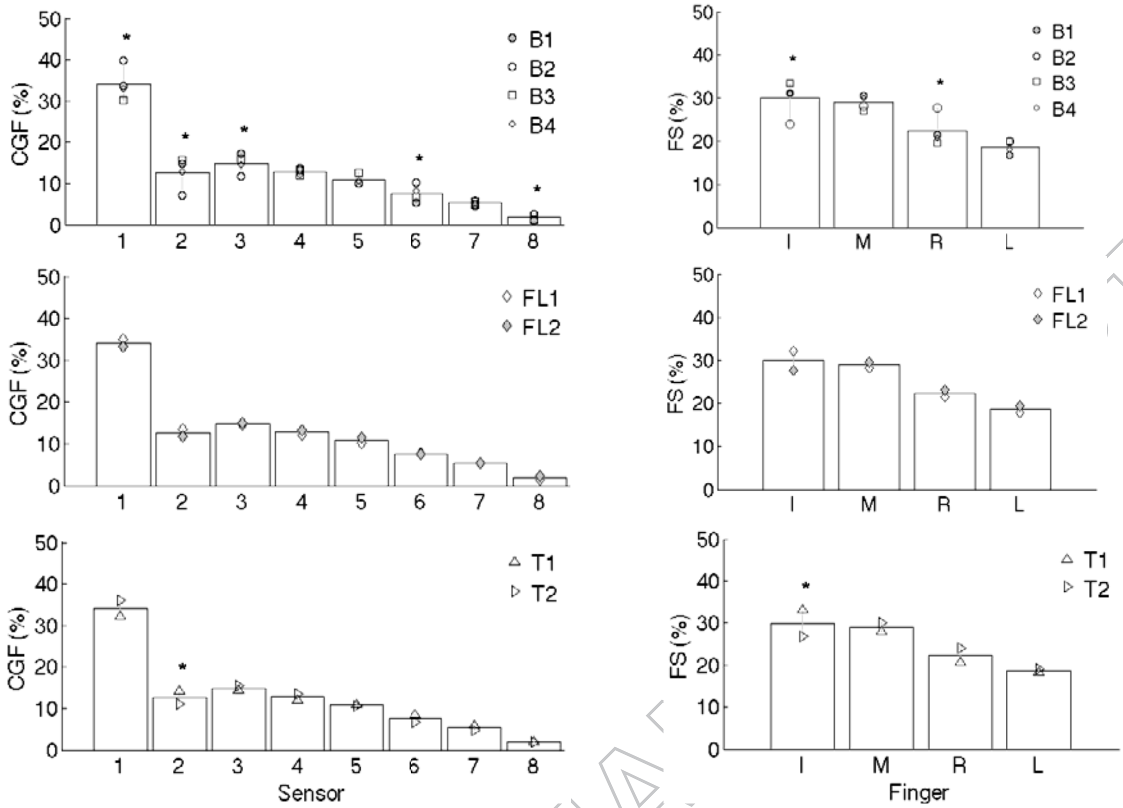


Figure 4. Mean MGF for transport (T1) and pouring (T2) tasks for each combination of bottle (B1: glass, B2, B3, B4: plastic) and filling level (FL1: low, FL2: high).



(a) (b)

Figure 5. Distribution of the grip force among hand zones: a) Contribution to grip force (CGF) for each sensor: DThumb (1), DIndex (2), DMiddle (3), DRing (4), DLittle (5), Palm (6), PIndex (7), PMiddle (8) b) Force sharing (FS) among fingers averaged across all the subjects and experiments: Index (I), Middle (M), Ring (R), Little (L). Bars represent mean values across all the experiments and the marginal means for each factor and level are represented with symbols, from top to down for 'bottle' (B1 to B4), 'filling level' (FL1, FL2) and 'task' (T1, T2), respectively. An asterisk in used to indicate statistical significance in the factor obtained from the ANOVAs.