Title: Lift observation conveys object weight distribution but partly enhances predictive lift planning

Running title: Weight distributions are partly encoded during observation

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Abstract

Observation of object lifting allows updating of internal object representations for object weight, in turn enabling accurate scaling of fingertip forces when lifting the same object. Here, we investigated whether lift observation also enables updating of internal representations for an object's weight distribution. We asked participants to lift an inverted T-shaped manipulandum with interchangeable center of mass in turns with an actor. Participants were required to minimize object roll during lifting by generating an appropriate amount of compensatory torque (i.e. 'lift performance') and were allowed to place their fingertips at self-chosen locations. The center of mass changed unpredictably every third to sixth trial performed by the actor and participants were informed that they would always lift the same weight distribution as the actor. Participants observed either erroneous (i.e. object rolling towards its heavy side) or skilled (i.e. minimized object roll) lifts. Lifting performance after observation was compared to lifts without prior observation and to lifts after active lifting, which provided haptic feedback about the weight distribution. Our results show that observing both skilled and erroneous lifts convey an object's weight distribution similar to active lifting, resulting in altered digit positioning strategies. However, lift performance on novel weight distributions was not improved after observing skilled lifts and only partly after observing erroneous lifts. In conclusion, these findings suggest that although observing motor errors and skilled motor performance enables updating of digit positioning strategy, only observing lifting errors enables less-than-optimal changes in predictive motor control when lifting objects with complex intrinsic properties.

New and noteworthy

Individuals are able to extract an object's size and weight by observing interactions with objects and subsequently integrate this information in their own motor repertoire. Here, we show that this ability is limited to simple features and does not extrapolate to more complex ones. Specifically, we highlighted that although individuals can perceive an object's weight distribution during lift observation they cannot embody this information when planning their own actions.

Keywords: Action observation; object lifting; dyadic interaction; motor planning

1. Introduction

Skilled object manipulation not only relies on haptic feedback but also on anticipatory mechanisms (Johansson and Westling 1988; Johansson and Westling 1984). It has been argued that when individuals perform hand-object interactions, they form an 'internal sensorimotor object representation' which can then be retrieved to predictively plan fingertip forces for future object manipulations (Johansson and Westling, 1988; Gordon et al., 1991).

Much evidence has been given about the pivotal function of hand-object interactions for the formation of an internal object representation (Baugh et al. 2012; Fu, Zhang, and Santello 2010; Gordon et al. 1991; Johansson and Westling 1984; Lukos, Ansuini, and Santello 2007). However, other studies have proposed that humans are able to generate similar representations when observing object lifting performed by others. For instance, previous studies have demonstrated that individuals are able to accurately estimate object weight during observed object lifting (Bingham 1987; Runeson and Frykholm 1981) and primarily rely on lift duration in doing so (Hamilton et al. 2007; Shim and Carlton 1997). Furthermore, it has been demonstrated that this information can also be used to update the sensorimotor representation and improve predictive lift planning: After observing someone making typical lifting errors (e.g. using too much force when lifting a light object caused by overestimating its weight), lifting errors made by the second individual can be reduced (Meulenbroek et al. 2007) or even eradicated (Reichelt et al. 2013). However, both these studies only focused on the observation of salient movement errors and not on skilled lift performance.

To our knowledge, only few studies compared how observing skilled or erroneous lifts mediate predictive object lifting. For instance, using the size-weight illusion, Buckingham et al. (2014) highlighted that predictive force scaling is improved after observing erroneous lifts compared to skilled ones: When participants had to lift a large, but unexpectedly light object for the first time, those who observed typical overestimation errors on the same object would make smaller lifting errors compared to those who observed skilled lifts. These findings and some of our previous results (Rens and Davare 2019) suggest that observing erroneous lifts conveys weight-related information better than skilled ones. In Rens and Davare (2019), participants were required to lift an object in turns with an actor. The object weight changed every n^{th} trial performed by the actor. Accordingly, participants could not predict the weight change but potentially rely on observing the actor's lifts to estimate object weight. Although our results showed that participants' lift performance improved after observing skilled lifts, this improvement was smaller compared to when they observed erroneous lifts. These findings were supported by a later study of ours: Even though observation of skilled lifting enabled participants to improve their own lift planning, they were still biased by the object size during lift execution (Rens et al. 2020).

It is important to note that the abovementioned studies only considered object weight and size for investigating how lift observation improves predictive lift planning in the observer. Critically, when an object's weight is asymmetrically distributed, meaningful object interactions not only require fingertip forces to be anticipatorily scaled to the object weight but also to the external torque (e.g. when content spill has to be avoided). Importantly, Lukos et al. (2007) demonstrated that individuals are also able to update their sensorimotor representation for an object's weight distribution, in turn predictively generating an appropriate amount of compensatory torque. Fu et al. (2010) extended on their findings by showing that individuals appropriately scale their fingertip forces in function of digit positioning: When digit positioning is constrained, individuals are able to accurately scale their fingertip forces according to the fixed contact points. Conversely, when digit positioning is unconstrained, individuals are also able to accurately scale their fingertip forces in function of their self-chosen contact points. As such, these findings suggest that individuals are able to generate many equally valid digit position-force coordination patterns to minimize object roll during object lifting.

To our knowledge, it has never been investigated whether lift observation can improve predictive lift planning for objects with an unknown weight distribution: Previous studies (Buckingham et al. 2014; Meulenbroek et al. 2007; Reichelt et al. 2013; Rens and Davare 2019) only investigated the effect of lift observation on object weight-driven predictive lift planning. Importantly, when lifting objects with asymmetrical weight distribution and digit positioning is not constrained, individuals need to accurately plan both their fingertip forces and positioning for minimizing object roll. Furthermore, a successful force-positioning coordination pattern depends on the interaction between predictive force planning and sensory feedback about digit placement: Although digit positioning is planned predictively, individuals still demonstrate trial-to-trial variability (Fu et al. 2010). As a result, it is necessary to update the planned fingertip forces in function of this digit positioning variability.

In the present study, we wanted to extend on the abovementioned literature by investigating (a) whether lift observation can convey critical information about an object's weight distribution and (b) to which extent observing either lifting performance type (erroneous or skilled) mediates predictive lift planning better. For this, we asked participants to grasp and lift an inverted T-shaped manipulandum with interchangeable center of mass in turns with an actor. Participants were required to minimize object roll during lifting by generating an appropriate amount of compensatory torque. In addition, participants were allowed to place their fingertips at self-chosen locations requiring them to scale their fingertip forces in function of this self-chosen positioning. As such, participants could generate many equally valid digit position-force coordination patterns. The center of mass changed unpredictably every third to sixth trial performed by the actor, but participants were informed that they would always lift the same weight distribution as the actor. As such, participants could potentially estimate the object's center of mass during observed object lifting, update their sensorimotor representation and subsequently plan their own lifting action correctly.

To investigate differences between performance types, we paired participants either with a naïve or informed actor. Naïve actors could not predict the center of mass change, making them unable to anticipatorily generate the appropriate amount of compensatory torque thus causing the inverted T-shape to roll towards its heavy side during lifting ('erroneous'). In contrast, the informed actor could predict the center of mass change and subsequently generate enough compensatory torque for minimizing object roll during lifting ('skilled'). As a result, the center of mass change was potentially indicated by either an erroneous (naïve actors) or skilled lift (informed actor). We hypothesized, in line with previous studies (Meulenbroek et al., 2007; Reichelt et al., 2013; Buckingham et al., 2014) that observation of lifting errors would improve predictive lift planning. In line with Rens and Davare (2019), we hypothesized that observation of skilled lifts would also improve predictive lift planning albeit in a smaller manner than observation of erroneous lifts.

2. Methods

2.1 participants

24 participants were recruited from the student body of KU Leuven (Belgium) and divided into two groups of 12 participants each. The first group (skilled observation group) consisted of 12 dyads in which each participant was paired with the experimenter (9 females and 3 males; mean age = 22.28 ± 0.65). The second group (error observation group) consisted of 6 dyads in which each participant was paired with another participant (9 females and 3 males; mean age = 21.38 ± 0.62). Participants in the second group did not know their paired partner in advance. All participants were right-handed (self-reported), had normal or corrected-to-normal vision, were free of neurological disorders and had no motor impairments of the right upper limb. The study was conducted in accordance with the declaration of Helsinki and was approved by the local ethical committee of the Faculty of Biomedical Sciences, KU Leuven. Participants gave written informed consent and were financially compensated. We excluded the data of one dyad (both actor and participant data) in the skilled observation group due to errors in data. As such, we had 12 participants in the error observation group and 11 in the skilled observation group.

2.2 data acquisition

For the present study, we used a custom-built carbon fiber ‘inverted T-shape’ grip-lift manipulandum (Arsalis, Belgium; for all object dimensions see: Figure 1). The manipulandum consisted of a horizontal basis and a vertical block to which two 3D force/torque (F/T) sensors were attached. On each force sensor a cover plate (height × width: 140 × 53 mm) with a central protruding surface (height × width: 140 × 20 mm) was mounted to block the view of the F/T sensors. Both protruding surfaces were covered with fine-grained sandpaper (p600) and the horizontal distance between them was 48mm. During the experiment, participants and experimenter were allowed to place their thumb and index finger freely (precision grip) but only on the protruding surfaces (i.e. ‘the graspable surfaces’). The horizontal basis of the manipulandum consisted of three compartments which enabled the placement of 3D-printed cuboids that were identical in appearance (height x width x depth: 55 x 35 x 40 mm).

Figure 1

The manipulandum, without cuboids, weighted 3.95 N. Two cuboids were hollow and weighted 0.24 N each, the third one was filled with lead particles and weighted 4.24 N. The total weight of manipulandum and cuboids was 8.67 N. Inserting the heavy cuboid in the left, center or right compartment would induce an external torque of - 245, 0 and + 245 Nmm respectively. Prior to the start of the study, the external torque was calculated in the following manner: For each center of mass, the manipulandum was held in the air with its base as horizontally as possible for 3 seconds. This was repeated 10 times (using different digit placement each repetition for when the heavy cuboid was in the side compartments). The amount of compensatory torque, i.e. amount of torque to keep the base horizontal, was calculated as the grand mean of the means of all repetitions for each center of mass location separately. Last, the external torque was defined as the opposite of the compensatory torque (e.g. compensatory torque for left center of mass = 245 Nmm, accordingly the external torque for the same center of mass = - 245 Nmm).

In the present study we used two ATI mini-40 SI-40-2 F/T sensors (force range: 40, 40 and 120 N for x-, y- and z-axes respectively; force resolution: 0.01 N; torque range: 2 Nmm; torque resolution: 0.0005 Nmm) (ATI Industrial Automation, USA). In addition, a ± 3 g three-dimensional accelerometer (ADXL335, Analog Devices, USA) was mounted on top of the vertical block, but hidden beneath the cover plates. Both F/T sensors and the accelerometer were connected to the same NI-USB 6221 OEM board (National Instruments, USA) which was connected to a personal computer. Data was acquired using a custom-written MATLAB script (Mathworks, USA) and sampled at 1Khz.

2.3 Experimental set-up

Dyadic set-up. Participants were comfortably seated in front of a square table with the lower arm resting on the table. The actor was seated at the left side of the table (seen from the participant's point of view) so that the participant and actor were angled 90 degrees towards each other. The grip-lift manipulandum ('inverted T-shape') was placed in between both individuals and positioned so that both individuals could grasp and lift the inverted T-shape comfortably (Figure 1). Participant and actor were asked to place their hands on a predetermined location on their side of the table to ensure consistent reaching throughout the entire experiment. Reaching distance was approximately 25 cm and required both individuals to use their entire right upper limb to reach for the inverted T-shape. When the actor would execute a trial, he/she would reach with their arm in front of the participant's upper body and lift the manipulandum from this position. We opted for placing actor and participant side by side (and not opposite) for two reasons: First, Mojtahedi et al. (2017) demonstrated that, when executing a dyadic interaction task simultaneously, subjects produce a smaller lifting error in a side-by-side configuration compared to a face-to-face one. Second, from this position, observed actor lifts had the same frame of visual reference as the lifts executed by the participants. Arguably, this would enhance participant's performance as it has been shown that modulation of corticospinal excitability during action observation is significantly more increased when observing actions from a first person point of view (Alaerts et al. 2009; Gallese et al. 2004). A transparent switchable screen (MagicGlass) was placed in front of the participant's face which was transparent during trials and returned opaque during inter-trial intervals. The switchable screen ensured that participants could not see the experimenter switching the cuboids between compartments, thus making them 'naïve' to the actual center of mass. Last, trials lasted 4 seconds and their onset was indicated with a neutral sound cue and the switchable screen (and glasses; see below) turning transparent. Trial length ensured that participant and actor had enough time to reach, grasp, lift and return the object smoothly at a natural place. Inter-trial interval was approximately 5 seconds during which the screen returned opaque and the center of mass could be changed.

Experimental groups. As mentioned above, participants were assigned to either the 'skilled observation group' or the 'error observation group'. Participants in the error observation group were paired with another participant and served as actors for each other (see: 'Experimental procedure'). To ensure that the ‘participant actors’ were also naïve to the center of mass change, they were required to wear transparent switchable glasses (PLATO, Translucent technologies) which behaved identically as the switchable screen. Participants in the skilled observation group were paired with the experimenter who served as the actor. One of the authors (G. Rens) served as the actor in the skilled observation group. Last, in the error observation group, the experimenter was seated opposite to the participant (and left of the actor) as he still needed to change the center of mass between trials.

2.4 Experimental procedure

General procedure. All participants performed the experimental task in two separate sessions with at least 24 hours between sessions. During the first session, participants gave written informed consent and were explained the experimental task and received the following instructions regarding object lifting: (1) lift the inverted T-shape to a height of approximately 5 cm at a smooth pace that is natural to you. (2) Only use your right thumb and index finger and only place them on the graspable surfaces (see: ‘Data acquisition’). (3) You are free to position your fingers on the graspable surfaces according to your own preferences and regardless of the actor’s positioning in the previous trial. (4) Keep the inverted T-shape’s base as horizontal as possible during lifting (i.e. ‘try to minimize object roll’). (5) The center of mass in your trials always matches the one in the actor’s preceding trial. In sum, participants were explained that they should try to estimate the center of mass during observed lifting and subsequently try to minimize object roll during their own lifts. Importantly, participants were explicitly explained they were free to select their own digit positioning. Arguably, using these instructions participants could develop their own digit force-position coordination strategy.

After task instructions, participants were given 3 practice trials for the symmetrical weight distribution and 6 practice trials for each asymmetrical distribution (left or right). For the practice trials on the central center of mass, participants were asked to always place the fingertips at the same height as it is not possible to minimize object roll with the fingertips positioned at different heights. In half of the practice trials for asymmetrical weight distribution, participants were asked to place their fingertips on the same height, i.e. ‘collinear’ positioning. In the other half, they were asked to place their fingertips at different heights, i.e. ‘noncollinear’ positioning (left center of mass: right thumb higher than right index finger; right center of mass: right thumb lower than right index). We emphasized these two different digit positioning to ensure that participants would understand the full scope of possibilities for minimizing object roll. Figure 2 illustrates how lifting related parameters on the asymmetrical weight distribution differ between skilled and erroneous lifts with collinear positioning as well as between skilled lifts with collinear and noncollinear positioning (For a discussion on these differences see the results section). Last, task instructions and practice trials were repeated at the start of the second session.

Experimental task. After task instructions, participants performed the object lifting task in turns with the actor. Actor and participant alternatingly performed a pseudo-random amount of 3 to 6 lifts on the same center of mass. Accordingly, the length of a sequence (i.e. sequential lifts on the same center of mass) varied between an even amount of 6 and 12 lifts (6 and 12 included). After a sequence was completed, the experimenter changed the center of mass for the next sequence. Due to the even amount of lifts per sequence, the person in the actor role always lifted the new center of mass first. To ensure that participants (and naïve actors) could not rely on sound cues (related to changing the center of mass) to locate the new center of mass, the experimenter always removed and replaced all 3 cubes after randomly rotating the inverted T-shape prior to each actor trial. These actions were never done before participant trials as they were explained that the center of mass in their trials would always match the one of the actor's preceding trial.

Experimental task in the skilled observation group. During the alternating task, the experimenter (the actor for this group) and participant performed 20 transitions from the central center of mass to each side. The experimenter lifted 10 center of mass sequences on each side with his fingertips placed collinearly and 10 with his fingertips placed noncollinearly. We decided on 10 sequences per condition based on Reichelt et al. (2013) who used 8 sequences. We included 2 more to take potential errors of the actor in account. We argued that experimentally manipulating the experimenter's digit positioning would enable us to investigate whether participants rely upon observed digit positioning to perceive the object's weight distribution. Importantly, as the experimenter was responsible for changing the center of mass, he should have always lifted the inverted T-shape skillfully (for an example see: Figure 3). As such, participants had to rely on other lifting parameters (such as digit positioning) to perceive the object's center of mass. After the sequence on the left or right side was completed, the experimenter changed the center of mass back to the central position to 'wash out' the internal representation for the asymmetrical weight distribution. In addition, 10 'catch transitions' in which the center of mass changed from side to side (and not side to center) were included to ensure that participants would not anticipate the typical change from side to central compartment. Transition orders were pseudo-randomized for each participant.

Importantly, the skilled observation group also performed the lifting task without actor to assess baseline sensorimotor memory effects (for example see: Johansson and Westling, 1984). This condition was included to investigate the magnitude of the lifting errors participants would make in the absence of lift observation. In this no observation condition participants performed 10 transitions from the center to each side and 5 catch transitions. Similar to the alternating task, the experimenter changed the center of mass every 3rd to 6th trial performed by the participant. The alternating (with actor) and no observation condition (without actor) were split over 4 and 2 experimental blocks respectively. Participants performed 2 alternating and 1 no observation block in one session and the other blocks in the second session. Participants started or ended one session with the no observation block to counter-balance order effects across participants. Participants received a short break between blocks. Last, the lifting sequences were equally distributed over all blocks. That is, each of the 4 blocks of the alternating lifting task consisted of 5 center of mass transitions to each side. In addition, in each block and for each side, participants observed the actor using each digit positioning type either 2 or 3 times (due to 10 trials per condition not being divisible over 4 blocks).

Experimental task in the error observation group. In addition to general instructions, participants in the error observation group were also explained that both of them would perform the participant and actor roles. Each participant performed 10 center of mass changes from the central to each side position and 5 catch transitions in each role, i.e. once as actor and once as participant. As such, participants performed 20 'experimental' and 10 catch transitions for both roles combined. As actors were naïve to the center of mass change, they could not anticipate the center of mass change causing them to not generate the appropriate amount of compensatory torque and having the object roll towards its heavy side. Importantly, because actors in this group were naïve we could not experimentally manipulate their digit positioning as we did in the skilled observation group. Because of this, the error observation group observed only half the amount of transitions compared to the skilled observation group [error observation group: 10 central to side transitions; skilled observation group: 20 central to side transitions (10 for collinear digit placement and 10 for noncollinear digit placement condition)]. Last, we did not include a no observation condition in the error observation group as the trials of participants in the actor role could be used as the 'no observation condition' to investigate baseline sensorimotor memory effects (for example see: Reichelt et al. 2013). To end, participants of the error observation group performed 4 experimental blocks of which 2 as actor and 2 as participant, spread over 2 sessions. Participants received short breaks between each block. Each participant started one session as actor and the other one as participant, switching seats within sessions when changing roles. Before participants performed as actor, they were given the same practice trials to get familiarized with their new seating. Due to this set-up, participants knew that the center of mass change would always happen first to the participant in the actor role. Accordingly, ‘actor participants’ were also explicitly asked to not guess or try to predict the center of mass change. During breaks and until the end of the second session, participants were not allowed to discuss the experiment with each other.

2.5 Data analysis

Data collected with the F/T sensors and accelerometer were sampled in 3 dimensions at 1000 Hz and smoothed using a fifth-order Butterworth low-pass filter (cut-off frequency: 15 Hz). On each force sensor, grip force (GF) was defined as the exerted force perpendicular to the normal force (Y-direction on Figure 1) and load force (LF) was defined as the exerted force parallel to the normal force (X-direction on Figure 1). Digit center of pressure was defined as the vertical coordinate (X-direction on Figure 1) of the center of pressure of the finger on the graspable surface attached to each force sensor and was calculated from the force and torque components measured by the respective F/T sensor relative to its frame of reference. For each sensor, the center of pressure was computed with formula 1.

$$\mathrm{COP} = \frac{(\mathrm{T_y} - \mathrm{F_x}\ \delta)}{\mathrm{F_z}} \tag{1}$$

In formula 1, COP = center of pressure; T_y = Torque in the Y-direction, F_x = Force in the X-direction, F_z = Force in the Z-direction, δ = cover plate thickness (1.55 mm). Using the digit center of pressure, we could also compute the compensatory torque. Compensatory torque was defined as the net torque generated by an individual to offset the external torque (i.e. to minimize object roll) caused by the object’s asymmetrical weight distribution. Compensatory torque was computed with formula 2 (we refer the reader to the supplementary materials of Fu et al., 2010 for the explanation of the formula).

$$\mathrm{T_{comp}} = \frac{\mathrm{d}}{2} \times (\mathrm{LF_{thumb}} - \mathrm{LF_{index}}) + (\mathrm{COP_{thumb}} - \mathrm{COP_{index}}) \times \mathrm{GF_{average}} \tag{2}$$

In formula 2, T_{comp} = Compensatory torque, d = horizontal distance between the digits (48 mm; Figure 1; Y-direction), $LF_{thumb/index}$ = Load force generate by the thumb and index finger respectively, $COP_{thumb/index}$ = center of pressure of the thumb and index finger respectively, $GF_{average}$ = averaged amount of GF exerted by the thumb and index finger.

To investigate the effects of lift observation on the participants’ performance, we used the following variables: Digit positioning difference, defined as the difference between the COP of the thumb and the index finger (positive values indicate a thumb placement higher than that of the index finger) and compensatory torque. We included difference in digit positioning to investigate whether the error and skilled observation groups used a different digit positioning strategy after lift observation. In addition, we emphasized compensatory torque as our key indicator of performance as (a) it results from the combination of grip and load forces as well as digit positioning and (b) because we explicitly asked participants to minimize object roll during lifting (i.e. 'task goal'). For the actors, we also included total grip force and load force difference (analogue to digit positioning difference; LF thumb minus LF index finger) at lift onset to explore potential differences in observed lift performance. In line with Fu et al. (2010), digit positioning was extracted at early object contact and the other parameters (compensatory torque, load force difference and total grip force) were extracted at lift onset. Early object contact was defined as total GF > 1 N to ensure that proper contact was established with both fingertips. Lift onset was defined as the first peak in the vertical acceleration (X-direction on Figure 1) between object contact and 200 ms after object lift off (defined as total LF = object weight).

Last, we did not expect relevant differences for lift performance between the left and right asymmetrical weight distribution (i.e. similar values for compensatory torque on either weight distribution) and also not for the symmetrical weight distribution depending on whether the previously lifted weight distribution was left or right asymmetrical. Moreover, we were not interested in whether lift performance differed between the left and right sides, but rather whether lift observation can improve predictive lift planning when lifting an unexpected asymmetrical or symmetrical weight distribution. In addition, potential statistical differences between sides could be caused by the hidden multiplicity of multiple testing (Cramer et al. 2016). Because of these reasons, we decided to pool our data for 'side'. That is, we pooled lift performance for the asymmetrical weight distributions (center of mass change to left or right) and we pooled for the symmetrical weight distribution (center of mass change from left or right). To ensure that pooling would not eradicate all effects (e.g. compensatory torque generated clockwise or counterclockwise is positive and negative respectively; Figure 1), we reversed the sign for compensatory torque, digit positioning difference and load force difference for when the center of mass changed to or from the right side. For the two latter parameters, positive values for the respective parameters indicate that (1) the finger on the heavy side is positioned higher than the finger on the light side and (2) the finger on the heavy side generates more load force than the finger on the light side. Importantly, uniquely for the symmetrical weight distribution, positive values indicate that the fingertip, previously on the heavy side, is positioned higher/generates more load force than the fingertip that was previously on the light side.

2.6 Statistical analysis

When the center of mass is on either side (i.e. ‘asymmetrical weight distribution’), participants need to generate the appropriate amount of compensatory torque to offset the external torque and minimize object roll. In contrast, when the center of mass is in the middle (i.e. ‘symmetrical weight distribution’), participants need to minimize object roll by not exerting any compensatory torque. Considering that these ‘task goals’ are different (asymmetrical: generate compensatory torque; symmetrical: do not generate compensatory torque), we analyzed lift performance separately for the asymmetrical and symmetrical weight distributions. All statistical analyses were performed in SPSS statistics version 25 (IBM, USA) and are described below.

Lifting performance of the actors. To investigate potential differences in the actors’ lifting performance, we performed the following analysis on each of the four included lifting parameters separately. For the actors, we included their third lift on the ‘old’ weight distribution and their first lift on the ‘new’ unexpected weight distribution. In line with Rens and Davare (2019), we did not use the last lift, but the third one. As the actors (and participants) would lift a given weight distribution 3 to 6 times, we decided to use the last lift of the consistent repetition (3rd lift) rather than the actual last lift. For instance, when the weight distribution changed from left asymmetrical to symmetrical, we included the actors third lift on the ‘old’ asymmetrical weight distribution and their first lift on the ‘new’ symmetrical weight one. This approach allowed us to investigate whether actors would appropriately update their predictive object lifting command for the novel weight distribution by lifting the new weight distribution differently than the old one. We did not include the actors’ second lift on the new weight distribution as the observing participants might have only relied on lift observation to plan their first lift and afterwards relied entirely on haptic feedback from their previous lift to plan upcoming lifts.

Considering that we had an incomplete factorial design based on our experimental groups, we decided to use linear mixed models (LMMs). We included the factor GROUP (skilled or error observation groups), DISTRIBUTION (old weight distribution and new weight distribution) and OBSERVATION (skilled noncollinear, skilled collinear, error observation). We included GROUP and DISTRIBUTION as main effects as well as their interaction effect GROUP X DISTRIBUTION. Due to each group observing only one lifting performance type (skilled lifts or lifting errors), OBSERVATION was added as a factor nested within GROUP (i.e. OBSERVATION$_{GROUP}$). Last, we also included the interaction effect DISTRIBUTION X OBSERVATION$_{GROUP}$

Lifting performance of the participants. To investigate the participants' lifting performance, we included their first and second lift on the new, unexpected weight distribution. In line with Rens and Davare (2019) and Reichelt et al. (2013), the potential effects of lift observation on predictive lift planning can be investigated by comparing lift performance after lift observation with lift performance after having haptic feedback about the actual object properties. Accordingly, here we were not interested in whether participants plan their lift differently for the new weight and old weight distribution, but rather whether they plan their lift for a new weight distribution similarly after lift observation or haptic feedback. Similar to our analyses for the actors' lift performance, we included the same factors GROUP and OBSERVATION. Importantly, there are two major differences with the actors' analyses. First, the factor DISTRIBUTION has been termed 'REPETITION' here (first or second lift on the new weight distribution), as both included lifts were performed on the same weight distribution. Second, the factor OBSERVATION consists of four levels here, i.e. skilled noncollinear, skilled collinear, error observation and also 'no observation'. Conversely, we included the same effects in the LMMs for the participants but having DISTRIBUTION being replaced by REPETITION and one extra level for OBSERVATION. Last, we did not include the third lift on the novel weight distribution as Fu et al. (2010) showed that predictive lift planning on an object with unexpected weight distribution improves from the first to second lift but not anymore from the second to third one which was supported by our preliminary analyses including this lift.

To end, because actors and participants performed two separate sessions (both groups) and switched roles (only error observation group), we investigated day and order effects. As these preliminary analyses did not reveal any relevant significant differences, we also decided to pool our data across sessions and experimental blocks. Finally, for all LMMs, we decided to include the mixed model covariance structures as first-order autoregressive based on the assumption that the correlation in residuals between factor levels was identical across levels. For the actors' LMMs we included the actors as subjects in the model (same actor for the skilled observation group and 12 unique actors for the error observation group). For the participants' LMM we included the participants as subjects in the model (11 participants in the skilled observation group and 12 participants in the error observation group). In each LMM, we also included the intercept. We used type III sum of squares and Maximum Likelihood (ML) for mixed model estimation and Bonferroni for pairwise comparisons. All data is presented as the mean ± standard error of the mean (SEM).

3. Results

In the present study, we aimed to investigate whether individuals are able to perceive an object's weight distribution during observation of object lifting and subsequently use this information to update their own predictive lift planning. Participants performed an object lifting task in turns with an actor and were asked to lift the object as skillfully as possible (i.e. minimize object roll by generating the appropriate amount of compensatory torque). Conversely, lifting was performed erroneously when an individual exerted an incorrect amount of compensatory torque. Participants were separated over two groups and paired with specific actors. The skilled observation group was paired with the experimenter ('informed actor') who could anticipate the center of mass change and would lift the object skillfully. Participants in the error observation group were paired with other participants from this group and served as actors for each other. The actors in the error observation group could not anticipate the center of mass change and were thus 'naïve' ('naïve actors'). Finally, participants could potentially rely on observed lifting to estimate the object's weight distribution and subsequently plan their own lifts correctly.

Traces of the different lifting parameters when skillfully and erroneously lifting the asymmetrical weight distribution are shown in Figure 2. Lift performance is shown in Figure 2A. When an individual correctly plans to lift an asymmetrical weight distribution, they will predictively generate compensatory torque during lifting (Figure 2A blue and green traces; i.e. 'skilled lifts'). In contrast, when an individual expects a symmetrical weight distribution, they will not plan for generating compensatory torque. Accordingly, the latter lift is planned incorrectly for an asymmetrical weight distribution (Figure 2A red trace, i.e. 'error lift'). As such, an individual's expectations of the object's weight distribution can be probed by quantifying the amount of compensatory torque they generated.

Importantly, generating compensatory torque relies on generating a valid digit positioning – (load) force coordination pattern (for a detailed explanation see Fu et al. 2010). The blue traces on Figure 2B and 2C resembles an individual skillfully lifting an asymmetrical weight distribution when placing the fingertips on the same height. As the vertical height difference between the fingertips is small (Figure 2B blue trace), the fingertip on the heavy side has to generate more load force than the finger on the light side (Figure 2D blue trace). Conversely, the green traces on figure 2B and 2D resembles an individual skillfully lifting an asymmetrical weight distribution with noncollinear positioning (i.e. fingertip on heavy side positioned higher than fingertip on light side). Due to the vertical height difference between the fingertips (Figure 2B green trace), the fingertip on the heavy side does not have to generate more load force than the fingertip on the light side (Figure 2D green trace). Last, when an individual incorrectly expects a symmetrical weight distribution, they will position their fingertips on the same height (Figure 2B red trace). As a result, the fingertip on the heavy side should generate more force than the one on the light side. However, as they incorrectly planned their lift, this load force difference between the fingertips will be generated slower compared to when they correctly anticipated the asymmetrical weight distribution (i.e. the difference in load force difference between the blue and red trace in Figure 2D which is analogue to the difference for compensatory torque in Figure 2A).

Figure 2

3.1 Center of mass change from symmetrical to asymmetrical

3.1.1 Actor's lifting performance

Based on the difference in naivety between the informed and naive actors, we expected that the informed actor would lift the asymmetrical weight distributions significantly better than the naive actors. As mentioned before, we included their last (i.e. third) lift on the 'old' symmetrical weight distribution and their first lift on 'new' the asymmetrical one. Arguably, if the actors' lifting parameters when lifting the asymmetrical weight distribution were similar to those when lifting the symmetrical one, this would indicate that the actors would predictively plan their lift for the symmetrical weight distribution, thus erroneously for the new asymmetrical one. Although we included only the first lift on the new weight distribution, please note that the naive actors' performance is the same as the error observation group's performance in the 'no observation condition'. Accordingly, the naïve actors' repeated performance (first and second lifts) on the asymmetrical weight distribution could be found there. To end, for the actors' performance we included (1) compensatory torque, as primary proxy of lift performance (i.e. minimizing object roll; Fu et al., 2010), (2) digit positioning, for investigating the informed actor's compliance with task instructions, and (3) total grip force and (4) load force difference as these force parameters have been considered indicative of object weight (Alaerts, Swinnen, and Wenderoth 2010; Hamilton et al. 2007) and could potentially convey similar information about an object's weight distribution. Last, the actor's lifting performance can be found in Figure 3.

Figure 3

Compensatory torque at lift onset. As can be seen in Figure 3A, the informed actor knew that the weight distribution would be asymmetrical, enabling him to increase the compensatory torque he generated (old symmetrical: mean = 2.90 ± 2.96 Nmm; new asymmetrical: mean = 181.59 ± 4.95 Nmm; *p*

< 0.001) while the naïve actors, blind to this change, could not do so (old symmetrical: mean = 22.98 ± .47 Nmm; new asymmetrical: mean = 17.39 ± 2.77 Nmm; $p = 1.00$) (DISTRIBUTION X GROUP: $F_{(1,144)} = 43.26$, $p < 0.001$). As a result, the informed actor generated more compensatory torque for the asymmetrical weight distribution than the naïve ones ($p < 0.001$) substantiating their difference in naivety based on our experimental set-up. Last, the informed actor generated similar compensatory torque on the asymmetrical weight distribution when using collinear (mean = 198.54 ± 6.62 Nmm) or noncollinear positioning (mean = 164.58 ± 7.44 Nmm; $p = 0.59$) (DISTRIBUTION X OBSERVATION$_{GROUP}$: $F_{(1,144)} = 0.20$, $p = 0.65$).

Digit positioning difference at early contact. When lifting the old symmetrical weight distribution, both the informed actor (mean = 1.45 ± 0.58 mm) and naïve ones (mean = -2.50 ± 1.01 mm) placed their fingertips similarly ($p = 0.23$) (*DISTRIBUTION X GROUP:* $F_{(1,144)} = 27.63$, $p < 0.001$). Again, as the naïve actors could not anticipate the new asymmetrical weight distribution, they did not alter their digit positioning (mean = 0.00 ± 0.40 mm; $p = 1.00$) (Figure 3B). In addition, our results show that the informed actor complied with task instructions: In the collinear condition (Figure 3B), he placed his fingertips similarly on the old symmetrical (mean = 1.45 ± 0.58 mm) and new asymmetrical weight distributions (mean = 2.59 ± 1.58 mm; $p = 1.00$) (DISTRIBUTION X POSITION$_{GROUP}$: $F_{(1,144)} = 75.21$, $p < 0.001$). When instructed to use noncollinear positioning on the new asymmetrical weight distribution, the informed actor placed his fingertips significantly further apart (mean = 39.73 ± 1.42 mm) compared to himself in all other conditions (*all* $p < 0.001$).

Total grip force at lift onset. The naive actors used similar amounts of grip forces when lifting the old symmetrical (mean = 21.22 ± 1.33 N) and new asymmetrical weight distributions (mean = 18.71 ± 1.04 N; $p = 1.00$) (Figure 3C). Similarly, when the informed actor was instructed to use collinear positioning (Figure 3C blue bars), he scaled his grip forces similarly when lifting the old symmetrical (mean = 24.41 ± 1.32 N) and new asymmetrical weight distributions (mean = 25.96 ± 0.86 N) ($p = 1.00$) (DISTRIBUTION X POSITION$_{GROUP}$: $F_{(1,144)} = 4.42$, $p = 0.37$). When the informed actor was instructed to change his digit positioning from collinear on the old asymmetrical weight distribution to noncollinear on the new asymmetrical one (i.e. the noncollinear condition; Figure 3C green bars), he scaled his grip forces similarly for the old symmetrical (mean = 18.47 ± 0.69 N) and new asymmetrical weight distributions (mean = 14.82 ± 0.76 N; $p = 1.00$). To end, the informed actor scaled his grip forces on average lower in the noncollinear (green bars) than in the collinear condition ($p = 0.02$) (POSITION$_{GROUP}$: $F_{(1,144)} = 9.06$, $p = 0.003$).

Load force difference at lift onset. As shown by the blue bars in Figure 3D, when the informed actor lifted the new asymmetrical weight distribution he scaled his load forces higher with the fingertip on the heavy side (mean = 3.49 ± 0.23 N) compared to when he lifted the old symmetrical weight distribution with the same digit positioning (mean = 0.49 ± 0.42 N; p < 0.001) (DISTRIBUTION X $\text{POSITION}_{\text{GROUP}}$: $F_{(1,144)} = 26.36$, $p < 0.001$). When the informed actor changed his digit positioning for the weight distributions, his load force difference was lower when lifting the new asymmetrical weight distribution noncollinearly (mean = -2.00 ± 0.24) compared to lifting the old symmetrical one collinearly (mean = -0.89 ± 0.25 N; $p = 0.04$) (Figure 3D green bars). Last, in line with our findings for the other lifting parameters, the naïve actors had similar load force differences when lifting the old symmetrical (mean = 1.07 ± 0.27 N) and new asymmetrical weight distributions (mean = 0.35 ± 0.09 N; p = 1.00) collinearly.

In sum, these lifting parameters substantiate our experimental set-up. That is, when the naïve actors repeatedly lifted the symmetrical weight distribution (their third lift on the symmetrical weight distribution), their lifting parameters did not differ significantly from those in their first lift on the unexpected asymmetrical weight distribution. In contrast, as the informed actor could predict this change, his lifting parameters (most importantly compensatory torque) differed significantly when lifting the symmetrical and asymmetrical weight distributions.

3.1.2 Participants' lifting performance

To investigate potential improvements in predictive lift planning, we compared the participants' lift performance in their first lift on the new weight distribution with their second ones. Logically, in their second lift participants could rely on haptic feedback. Thus, this comparison enabled us to investigate how lift planning based on observation compares to lift planning based on haptic feedback. Last, the participants' lifting performance on the asymmetrical weight distribution can be found in the top row of Figure 4.

Figure 4

Only error observation improves predictive lift planning of compensatory torque. As shown in Figure 4A, both groups exerted higher compensatory torques after having their internal object representation for the asymmetrical weight distribution updated through haptic feedback (second lifts pooled across conditions; mean = 202.33 ± 3.37 Nmm) compared to when they had no haptic feedback (first lifts pooled across conditions; mean = 59.77 ± 4.19 Nmm; p < 0.001) (REPETITION: $F_{(1,240)} = 636.67$, *p*

$< 0.001)$. This effect of repetition is potentially driven by pooling of the 'no observation' and observation conditions. To investigate this possibility, we explored the significant effect of REPETITION X $OBSERVATION_{GROUP}$ *($F_{(3,240)} = 16.78$, $p < 0.001$).* Interestingly, when the error observation group lifted the asymmetrical weight distribution for the first time, they generated significantly more compensatory torque after observing an erroneous lift (mean = 114.66 ± 8.46 Nmm) compared to having no observation (mean = 17.38 ± 2.77 Nmm) (right side of Figure 4A). However, observing lifting errors did not improve predictive lift planning equally well as haptic feedback as lift performance of the error observation group was significantly better in the second lift after both error observation (mean = 208.39 ± 9.64 Nmm; p < 0.001) and no observation (mean = 201.57 ± 6.71 Nmm; $p < 0.001$). In contrast, in the skilled observation group, we did not find any evidence that observing skilled lifts on an asymmetrical weight distribution improves predictive lift planning. In their first lift after the unexpected change in weight distribution, participants generated similar amounts of compensatory torque after no observation (mean = 34.60 ± 9.89 Nmm) and after observing a skilled lift with noncollinear (mean = 84.69 ± 10.99 Nmm; $p = 0.47$) or collinear digit positioning (mean = 42.20 ± 8.44 Nmm; $p = 1.00$). Moreover, performance in these first lifts was significantly worse compared to their second lifts (pooled across conditions: mean = 200.38 ± 4.78 Nmm; for each within-condition comparison: $p < 0.001$). In conclusion, these findings indicate that only error observation improves predictive lift planning on asymmetrical weight distributions albeit to a lesser extent than tactile feedback.

Digit positioning strategies are similar after both haptic and visual feedback. The black bars in Figure 4B show that, in the absence of lift observation, both groups positioned their fingertips more noncollinearly in their second lift (skilled observation group: mean = 27.58 ± 2.78 mm; error observation group: mean = 21.75 ± 1.84 mm) compared to their first one (skilled observation group: mean = 0.68 ± 0.45 mm, $p < 0.001$; error observation group: mean = 0.00 ± 0.40 mm; $p = 1.00$) (REPETITION X $OBSERVATION_{GROUP}$: $F_{(3,240)} = 13.13$, $p < 0.001$). As such, both groups preferred to position their fingertips further apart when they had knowledge about the object's weight distribution based on haptic feedback. The skilled observation group tended to imitate the informed actor's digit positioning in their first lift after lift observation. They positioned their fingertips noncollinearly (mean = 26.15 ± 1.74 mm) or collinearly (mean = 2.65 ± 1.76 mm) after observing the informed actor using noncollinear or collinear positioning respectively. Accordingly, in their first lift of the noncollinear condition, the skilled observation group positioned their fingertips significantly further apart compared to their first lifts in the other conditions (*both* $p < 0.001$; Figure 4B). Furthermore, this noncollinear positioning was similar to the one the skilled observation group used in their second lift of the no observation condition ($p = 1.00$), indicating that observing skilled lifts with noncollinear digit positioning enabled participants to rely on the same digit positioning strategy they would use when having haptic feedback. The error observation group also positioned their fingertips more noncollinearly after observing a lifting error (mean = 19.45 ± 2.23 mm) compared to having no observation ($p < 1.00$). Moreover, this digit positioning strategy was similar to the one they relied upon when having haptic feedback (second lift of the no observation condition; $p = 1.00$; Figure 4B). By and large, these findings indicate that the error observation group adjusted their digit positioning strategy similarly after having haptic or visual feedback about the object's weight distribution.

3.2 Center of mass change from asymmetrical to symmetrical

3.2.1 Actor's lifting performance

Although we were initially interested in whether lift observation can improve predictive object lifting on objects with an asymmetrical weight distribution, we included the center of mass change from asymmetrical to symmetrical for completeness. Here, we included the last (i.e. third) lift on the 'old' asymmetrical and the first lift on the 'new' symmetrical weight distribution. As the actors' data was intended to validate our experimental set-up, and results were similar to those in 'the center of mass change from symmetrical to asymmetrical', we will not discuss it in detail again. As such, all data of the informed and naïve actors can be found in Table 1.

However, for transparency, there is one compensatory torque finding that should discussed in detail. Both skilled and naive actors generated significantly less compensatory torque in their first lift on the new symmetrical weight distribution compared to their last lift on the old asymmetrical one (see Table 1; for each group: $p < 0.001$) (DISTRIBUTION X GROUP: $F_{(1,144)} = 29.01, p < 0.001$). However, when the informed actor changed from noncollinear positioning on the old asymmetrical weight distribution to collinear positioning on the new symmetrical one, he generated significantly less compensatory torque (mean = 29.61 ± 7.16 N) compared to himself when not changing his digit positioning (i.e. collinear on old asymmetrical weight distribution and then on new symmetrical one; mean = 111.81 ± 12.08 N; $p < 0.001$). These findings indicate that the informed actor was more adept at reducing the amount of compensatory torque when changing his digit positioning for the novel weight distribution.

3.2.2. Participants' lifting performance

Briefly, we investigated the participants' lift performance on their first and second lift on the symmetrical weight distributions (after it unexpectedly changed from asymmetrical) to investigate whether lift observation improves predictive planning. Again, the participants' lifting performance on the symmetrical weight distribution can be found in the bottom row of Figure 4.

Again, only error observation improves predictive lift planning of compensatory torque. As indicated in Figure 4C, the error observation group generated significantly less compensatory torque after error observation (mean = 64.62 ± 8.45 N) compared having no observation (mean = 140.19 ± 7.43 N) when lifting new unexpected symmetrical weight distribution *($p < 0.001$)* (REPETITION X OBSERVATION$_{GROUP}$: $F_{(3,240)} = 5.40, p < 0.001$). Importantly, this did not differ significantly from their lift performance in their second lift of the no observation condition (mean = 33.39 ± 3.92 N; $p = 0.19$). As such, the error observation group was able to lift the symmetrical weight distribution skillfully after observing a lifting error. In contrast, the skilled observation group was not able to generate significantly less compensatory torque after observing the actor switch from noncollinear positioning on the asymmetrical weight distribution to collinear positioning on the symmetrical one (mean = 79.72 ± 6.91 N; Figure 4C first green bar) compared to having no observation (mean = 127.52 ± 10.14 N; $p = 0.92$). In addition, when the actor did not change his digit positioning for the weight distributions (mean = 111.81 ± 12.08 N; Figure 4C first blue bar), the skilled observation group did not generate significantly less compensatory torque compared to the no observation condition ($p = 1.00$). In addition, the skilled observation group generated significantly less compensatory torque in their second lifts of each condition compared to the respective first lifts (*all* $p < 0.001$). These findings indicate that the skilled observation group was not able to generate the appropriate amount of compensatory torque after lift observation

Digit positioning strategies are similar after both haptic and visual feedback. Briefly, both groups placed their fingertip significantly further apart in their first lift on the unexpected symmetrical weight distribution (mean = 4.38 ± 0.47 mm) than in their second one (mean = -2.21 ± 0.54 mm; $p < 0.001$) (REPETITION: $F_{(1,240)} = 0.91, p = 0.44$). Although the effect REPETITION X GROUP was significant ($F_{(3,240)} = 4.42, p = 0.042$), the post-hoc analyses failed to reveal any relevant significant differences between groups (*all* $p > 0.46$). In conclusion these findings indicate that both groups changed their digit positioning from their first to second lift although earlier lift observation did not have any major effects.

Discussion

Previous studies (Meulenbroek et al., 2007; Reichelt et al., 2013; Buckingham et al., 2014; Rens and Davare, 2019) have substantiated that lift observation can mediate critical information about an object's weight. To extend on these studies, we investigated here, whether individuals can also perceive an object's weight distribution during observed object lifting and, again, use this information to appropriately update their motor command. Participants were required to lift an object with interchangeable center of mass in turns with an actor. The task goal consisted of lifting the object 'as skillfully as possible', i.e. minimize object roll by generating the appropriate amount of compensatory torque. Importantly, participants either observed skilled (i.e. minimized object roll) or erroneous lifts (i.e. non-minimized object roll) which could potentially convey critical information about the object's weight distribution. Importantly, our results indicate that individuals can extract information about an object's weight distribution from lift observation. Specifically, when participants observed lifting of a novel weight distribution which was erroneous or skilled with a novel digit positioning, they changed their digit positioning strategy. Furthermore, this visual feedback about the object's weight distribution drove participants to use the same digit positioning strategy as when they had haptic feedback. However, although participants could perceive the new weight distribution during lift observation, only observing lifting errors enabled participants to predictively generate the appropriate amount of compensatory torque. In addition, even though the error observation group performed better after lift observation, their performance was still worse compared to when they had haptic feedback. In conclusion, these findings suggest that observation of motor errors, but not skilled motor performance, drives changes in predictive motor control when lifting objects with complex intrinsic properties. However, these improvements are less-than-optimal when compared to predictive lift planning based on haptic feedback.

It has been well-established that observing lifting errors mediates object weight-driven predictive lift planning (Meulenbroek et al., 2007; Reichelt et al., 2013). That is, when two individuals have an incorrect expectation of object weight, the second individual will scale his forces more accurately to the actual object weight after observing the first one making a lifting error. Here, in contrast to these studies, lift performance was primarily quantified by digit positioning and the amount of compensatory torque participants generated. We focused on these parameters based on Fu et al (2010). First, they demonstrated that when individuals can freely choose their digit positioning, they place their fingertips further apart (more noncollinearly) when lifting asymmetrical weight distributions. Second, the amount of compensatory torque an individual generate is highly correlated with the amount of object roll. With respect to these parameters, our results show that the error observation group could perceive the object's weight distribution during lift observation: When participants lifted a novel weight distribution for the first time, their digit positioning strategy was similar compared to when they had haptic feedback about the actual weight distribution but different compared to when they could not predict the weight distribution (i.e. without lift observation or haptic feedback). Last, as the naïve actors in the error observation group could not anticipate the unexpected center of mass change, they did not place their fingertips according to their preferences as, for instance, they positioned their fingertips on the same height for the asymmetrical weight distributions. As such, it important to note that after lift observation, participants did not position their fingertips imitatively but rather by relying on an internally driven strategy. Critically, even though observation of lifting errors drove participants to update their digit positioning strategy, it did not enable them to lift the unexpected weight distribution skillfully. That is, after observing a lifting error, participants did perform better than without observation, but they did not generate similar amounts of compensatory torque compared to when they had haptic experience. To sum up, our findings show, in line with previous studies (Meulenbroek et al. 2007; Reichelt et al. 2013), that individuals are able to perceive intrinsic object properties during lift observation. However, our findings highlight that although lift observation conveys critical information about an object's weight distribution, it does not allow individuals to optimally update their motor command for intrinsic object properties that are more complex than object weight.

With specific interest to the observation of skilled lifting, Rens and Davare (2019) showed that observing skilled lifts can improve predictive lift planning, albeit in a smaller manner than observing lifting errors. Here, our results suggest that participants who observed skilled lifting imitated the actor's digit positioning: When the informed actor placed his fingertips on the same height or on different heights, participants positioned their fingertips similarly. As such, it is plausible that the skilled observation group relied likely on an imitative strategy whereas the error observation group relied on an internally selected position-force coordination pattern. With respect to minimizing object roll, our findings show that the skilled observation group was not able to lift the unexpected weight distribution skillfully after observing a skilled lift. That is, when participants lifted the unexpected weight distribution after observing a skilled lift, they generated similar amounts of compensatory torque compared to when they had no prior lift observation. In addition, after observing a skilled lift, they generated significantly less compensatory torque compared to when they had prior haptic experience. In conclusion, our findings suggest that skilled lift observation drives participants to rely on an imitative strategy with respect to digit positioning. Importantly, skilled lift observation did not allow participants to update their motor command for the actual weight distribution. As such, our results provide no evidence that skilled lift observation improves predictive lift planning for intrinsic object properties that are more complex than object weight.

As mentioned before, it has been well-established that individuals can update their internal object representation when observing lifting errors (Hamilton et al. 2007; Reichelt et al. 2013). In addition, Buckingham et al. (2014) and Rens and Davare (2019) demonstrated that observing lifting errors mediates object weight better than observing skilled ones. Arguably, superiority of observing erroneous lifts for mediating predictive motor planning is likely driven by the typical kinematic discrepancies between erroneous and skilled object lifting (Johansson and Flanagan 2009; Johansson and Westling 1988). Because of these discrepancies, lifting errors have been argued to be more ‘salient’ than skilled ones, that is, more indicative of actual object weight. In line with this notion, our findings suggest that lifting errors are also more indicative of an object’s weight distribution. In addition, Flanagan and Johansson (2003) demonstrated that individuals target their gaze during observation of hand-actions predictively towards the hand rather than responsively. Accordingly, it has been proposed that individuals anticipate movement components during action observation rather than simply monitoring the entire action sequence by itself. Our findings support these hypotheses: both the skilled and error observation groups updated their lifting strategy after observing a change in digit positioning or the object rolling towards its heavy side respectively. Arguably, this discrepancy between expected and observed lifting behavior drove participants to change their digit positioning strategy. In contrast, participants did not change their digit positioning when observing skilled lifts without a change in digit positioning. Presumably, both the unexpected change in digit positioning and object roll could be considered salient with respect to indicating a center of mass change although they do not optimally improve predictive lift planning.

It has been argued that action understanding relies, at least, partially on the putative human mirror neuron system (hMNS) (Rizzolatti et al. 2014). Mirror neurons, first discovered in macaque F5 (di Pellegrino et al. 1992), are similarly activated during execution and observation of the same actions. As such, mirror neurons mediate action understanding by ‘mapping’ observed actions onto the same cortical representations involved in their execution. In humans, these effects have been reproduced by applying single pulse transcranial magnetic stimulation (TMS) over the primary motor cortex (M1). The earliest work of (Fadiga et al. 1995) showed that corticospinal excitability (CSE) was similarly modulated when observing or executing the same action. In line with the mirror neuron theory, they argued that the motor system could be involved in action understanding. Consequently, action observation-driven modulation of CSE has been termed ‘motor resonance’. Recently, TMS studies in humans substantiated that motor resonance reflects movement features within observed actions. For example, Alaerts et al. (2010a, 2010b) demonstrated that, during lift observation, motor resonance is modulated by observed features indicative of object weight, such as intrinsic object properties (e.g. size), muscle contractions and movement kinematics. Specifically, CSE is increased when observing lifts of heavy compared to light objects. In line with these findings and the hMNS theory, it is possible that an individual's motor system encodes the object's weight distribution during lift observation. Indeed, in our study, the hMNS could have driven the skilled observation group to imitate the actor's digit positioning as Iacoboni (2005) argued the involvement of the hMNS in imitative behavior. In contrast, the motor system of the error observation group could have resonated the observed erroneous lifting performance, enabling them to understand this error resided within an incorrectly planned motor command and subsequently caused them to update their own motor command (Kilner 2012). However, it is interesting to note that, even though the hMNS might have caused our participants to alter their digit positioning strategy, it did not allow them to lift the novel weight distribution skillfully in their first attempt. As such, our findings suggest that the hMNS might not be able to encode intrinsic object properties that are more complex than object weight. In support of this notion, we recently demonstrated that activity within the hMNS is heavily influenced by top-down inputs from the posterior superior temporal sulcus (pSTS) based on contextual information (Rens et al. 2020). Accordingly, it is possible that the hMNS resonates to simple movement features object weight (e.g. digit positioning or object weight) but that its output is suppressed by top-down pSTS inputs. Furthermore, the research group of Santello (Fu et al. 2010; Lukos et al. 2007; Lukos et al. 2013) argued that, when individuals lift an object with unconstrained digit positioning, they generate an initial predictive digit positioning motor command. Subsequently fingertip forces are scaled in accordance with their actual digit positioning to generate the appropriate amount of compensatory torque. It is possible that the observer's motor system predominantly resonates digit positioning due to this hypothesized responsive nature of force scaling. However, future research is necessary to support this notion.

One of the limitations of the present study is that we did not measure object roll during the experiment. However, Fu et al. (2010) demonstrated that object roll and compensatory torque are strongly correlated. Because of this, we decided to only include compensatory torque as a key parameter to investigate predictive lift planning of the observers. In addition, our inverted T-shape object only consisted of three compartments for changing the weight distribution. Although, this is a small improvement to many of the observation studies using a dichotomous approach with two weights (for example see: Rens and Davare 2019; Buckingham and Gribble 2017; Reichelt et al. 2013), our set-up does not enable us to investigate whether participants discriminated between the three options or actually integrated the intrinsic object properties into their own internal object representation. For instance, Reichelt et al. (2013) demonstrated that individuals are also able to predictively plan their own lift significantly better after observing a lifting error but also after receiving a verbal cue indicating the object weight was changed. Accordingly, future studies could aim to increase task complexity (for instance see Schneider et al., 2019). A final limitation is that, although the informed actor performed significantly better than the naive actors, his performance was suboptimal as he did not generate the appropriate amount of compensatory torque at object lift-off. As such, it is likely that the skilled observation group was also able to perceive object roll during lift observation albeit in a smaller amount than the error observation group. Critically, although the informed actor's performance was imperfect, the large differences between our experimental groups indicate that differences between the observed lifting performance types did matter. Specifically, larger deviations from skilled lifting enabled participants to better plan their own lifts predictively.

In conclusion, in the present study, participants performed an object lifting task in turn with another individual who lifted either skillfully or erroneously. During the task, they were required to lift an object during which they had to minimize object roll by generating the appropriate amount of compensatory torque. Our results highlight that even though lift observation allows observers to perceive an object's weight distribution, only observation of lifting errors improve predictive lift planning albeit in a suboptimal manner. As such, our findings extend on previous studies (Reichelt et al., 2013; Rens and Davare, 2019) by showing that lift observation does not improve predictive lift planning equally well as haptic feedback for intrinsic object properties that are more complex than weight.

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Table

	Informed actor				Naïve actors	
	Old asymmetrical		New symmetrical		Old asymmetrical	New symmetrical
	Informed noncollinear	Informed collinear	Informed noncollinear	Informed collinear	Blind lift	Blind lift
Compensatory torque (Nmm)	216.53 ± 4.26	266.43 ± 5.43	29.61 ± 7.17	111.81 ± 12.08	207.23 ± 5.62	140.19 ± 7.43
Digit positioning difference (mm)	43.18 ± 1.59	16.25 ± 1.80	6.00 ± 1.03	6.38 ± 0.97	22.48 ± 1.79	5.94 ± 0.55
Total grip force (N)	14.10 ± 0.71	22.41 ± 0.84	18.95 ± 1.15	25.55 ± 1.49	21.18 ± 1.40	22.92 ± 1.55
Load force difference (N)	-1.26 ± 0.23	2.47 ± 0.37	-0.40 ± 0.33	0.85 ± 0.45	-0.03 ± 0.37	1.93 ± 0.21

Captions

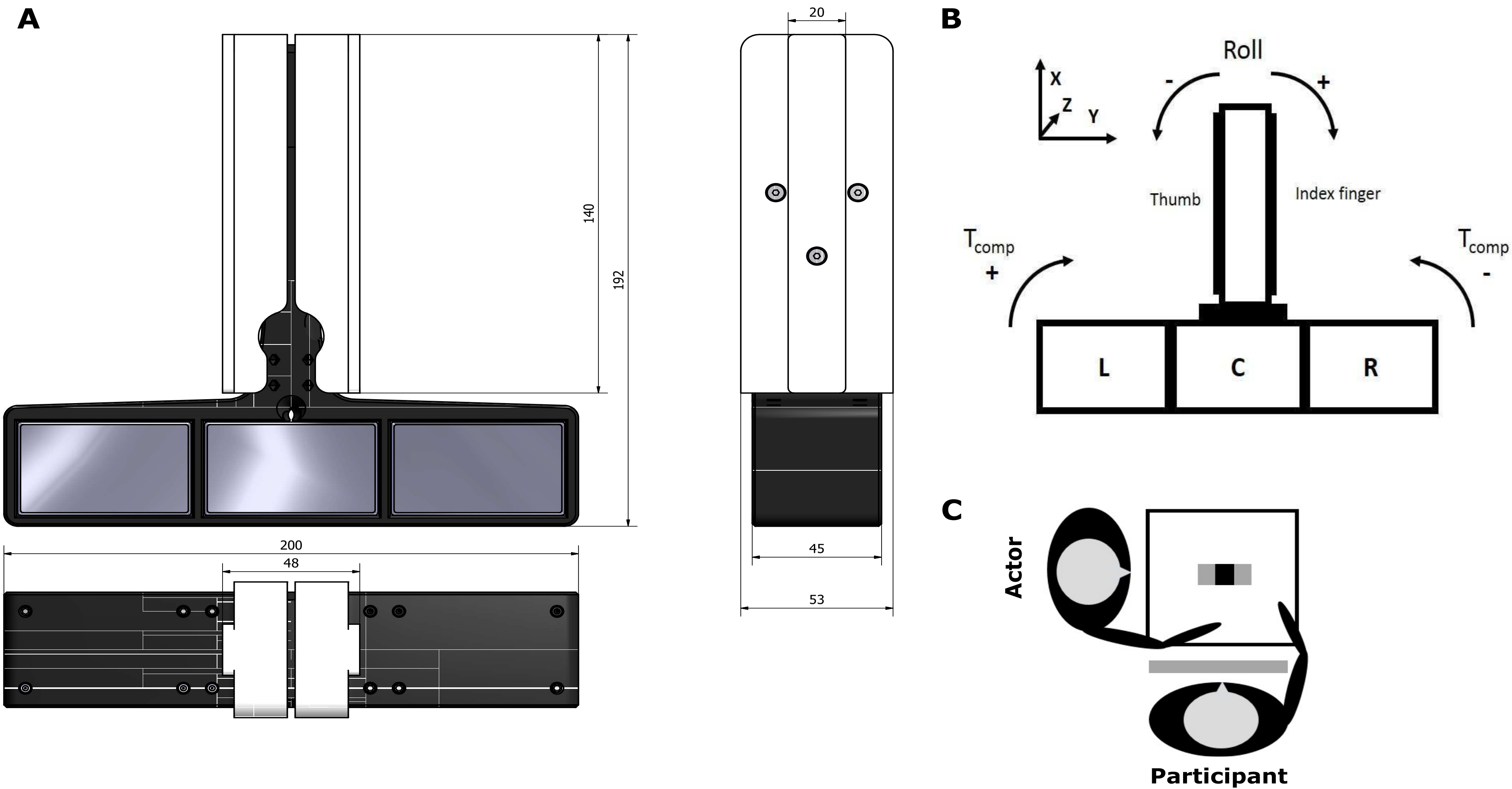
Table 1. The actors' lifting performance for old asymmetrical to new symmetrical. Values represent the lift performance of the informed actor (skilled observation group) and naïve actors (error observation group) in their first and second lift on the new symmetrical weight distribution. Values are presented as mean ± SEM. No statistics are shown in this table.

Figure 1. Manipulandum and set-up. A. Frontal, side and top down view of the 'inverted T-shape' manipulandum with dimensions (in mm). The manipulandum consisted of a vertical (white) component and a horizontal base (black). The horizontal base consisted of 3 compartments in which the 3D printed cuboids could be placed. **B.** Schematic drawing of the manipulandum with the three compartments indicated with L, C and R standing for left, center and right respectively. Counter clockwise and clockwise roll were defined as negative and positive respectively. Compensatory torque, i.e. torque generated by participants to offset object roll was defined as the inverse of object roll, i.e. positive and negative for clockwise and counter clockwise compensatory torque respectively. X, Y and Z indicate the frame of reference for the force/torque sensors in the vertical component. **C.** The participant and actor were seated next to each other at a table on which the manipulandum was positioned and a switchable screen was placed in front of the participant's face.

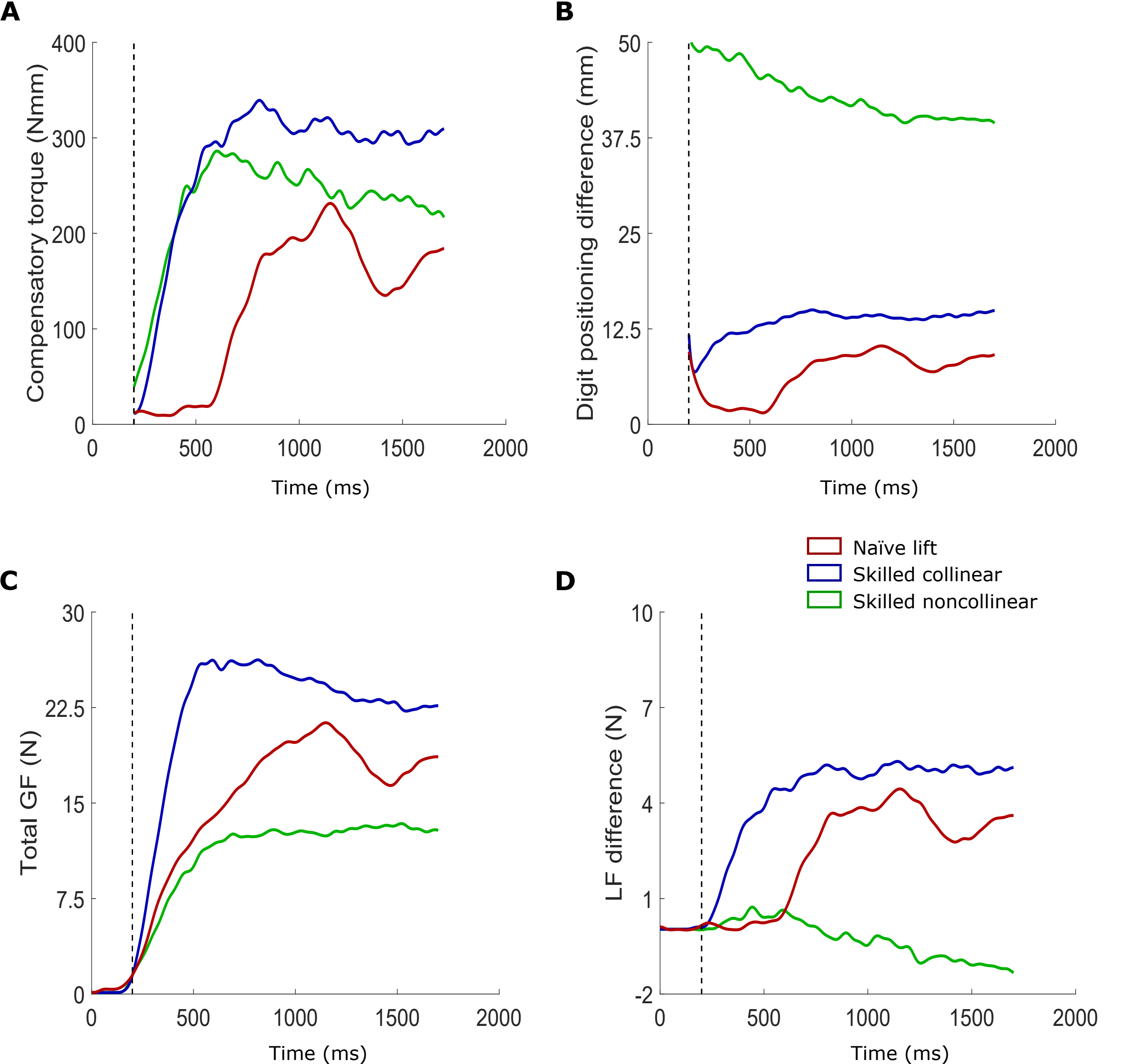
Figure 2. Representative traces when lifting the asymmetrical weight distribution. One lift example for each experimental condition when lifting the asymmetrical weight distribution. Typical traces showing the evolution of different parameter profiles over time for a skilled lift with fingertips positioned on the same height ('skilled collinear'), a skilled lift with fingertips positioned on different heights ('skilled noncollinear') and a naïve lift ('naïve lift') in which the individual incorrectly anticipated the weight distribution to be symmetrical. **A**. Compensatory torque (Nmm) generated by the individual to offset the external torque, induced by the asymmetrical weight distribution. **B.** Digit positioning difference (mm): vertical distance between the centers of pressure of the fingertips (position fingertip on heavy side - position fingertip on light side). **C.** Total amount of grip force (N). **D.** Difference in load force exertion (N) between the fingertips (load force fingertip on heavy side – load force fingertip on light side). The dashed black line represents early object contact. As compensatory torque and digit positioning difference are calculated based on early contact and are highly contaminated by noise before actual contact, we removed their values before early object contact.

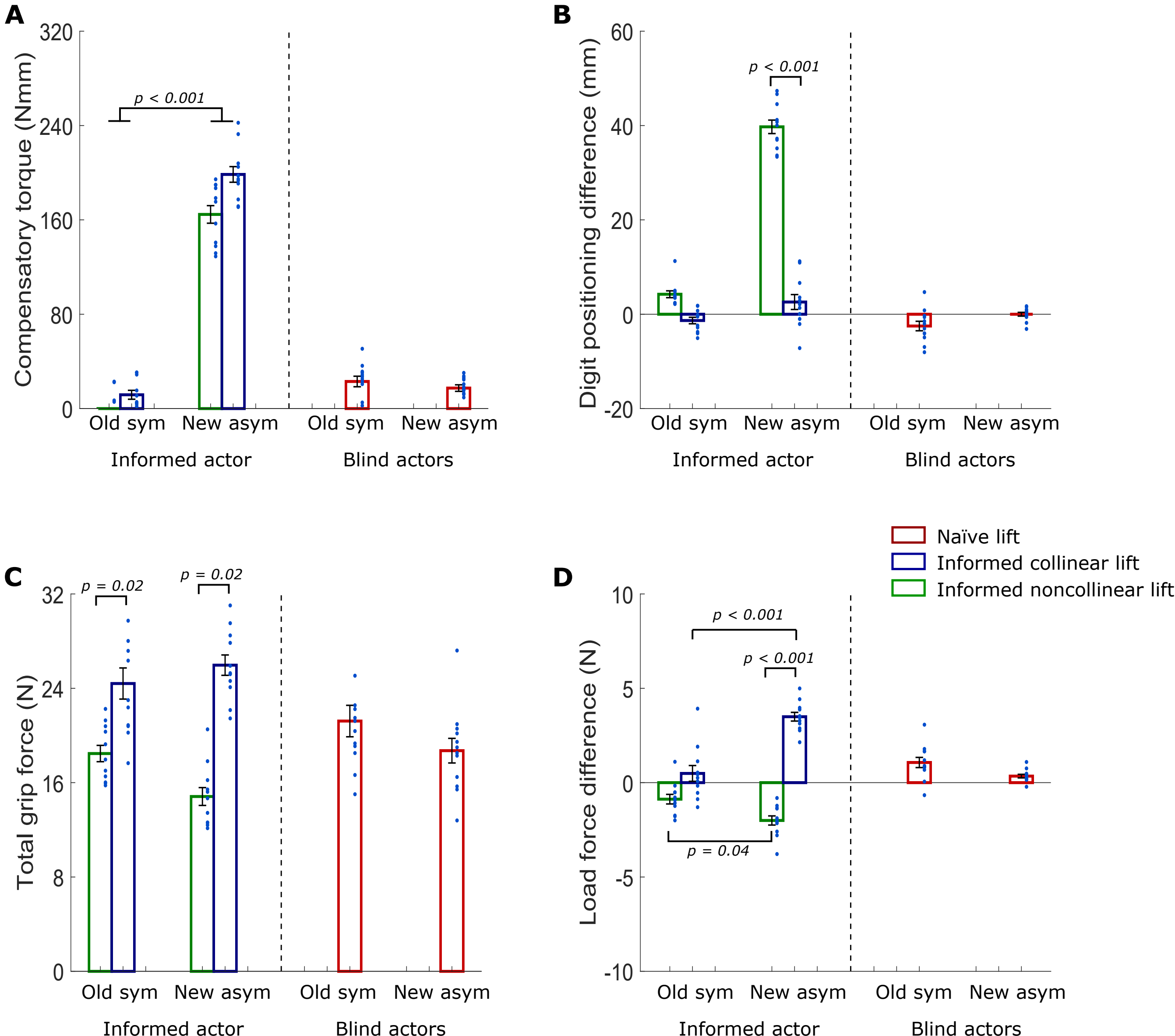
Figure 3. Lift performance of the actors. Lifting performance of the informed and naïve actors when the weight distribution changed from old symmetrical (‘Old sym’) to new asymmetrical (‘New asym’). Accordingly, the first bars (above ‘Old sym’) represent the actors’ third lift on the old symmetrical weight distribution and the second bars (above ‘ New asym’) represent the actors’ first lift on the new symmetrical weight distribution. **A.** Compensatory torque (Nmm). **B.** Digit positioning difference (mm). **C.** Total amount of grip force (N). **D.** Difference in load force exertion (N). **Red**: Lifting performance of the naïve actors who could not anticipate the weight distribution change (‘error observation’). **Blue:** Lifting performance of the informed actor, who could anticipate the weight distribution change, when positioning both fingertips on the same height when lifting both weight distributions (‘skilled observation collinear’). **Green:** Lifting performance of the informed actor when positioning both fingertips on the same height on the symmetrical weight distribution but on different heights when lifting the asymmetrical one (‘skilled observation noncollinear’). All data is presented as the mean ± SEM. Each circle (scatter) represents the lift performance of one actor in a given condition. Only within-actor group differences are shown on the figure.

Figure 4. Lift performance of the participant. Lifting performance of the skilled (‘skilled group’) and error observation groups (‘error group’) when the weight distribution changed from symmetrical to asymmetrical **(left)** or from asymmetrical to symmetrical **(right)**. For each group first and second lifts on the novel weight distribution are shown. **Top figures**. Compensatory torque (Nmm). **Bottom figures.** Digit positioning difference (mm). **Red**: Lifting performance of the error group after observing a lifting error by the error actors who could not anticipate the weight distribution change (‘error observation’). **Blue:** Lifting performance of the skilled group when observing the skilled actor lifting both weight distributions with collinear digit positioning (‘skilled observation collinear’). **Green**: Lifting performance of the skilled group when observing the skilled actor lifting the symmetrical and asymmetrical weight distributions with collinear and noncollinear digit positioning respectively (‘skilled observation noncollinear’). **Black:** Lifting performance of each group when lifting without prior observation (‘without observation’). All data is presented as the mean ± SEM. Each circle (scatter) represents the lift performance of one participant in a given condition. Only within-group differences are shown on the figure.

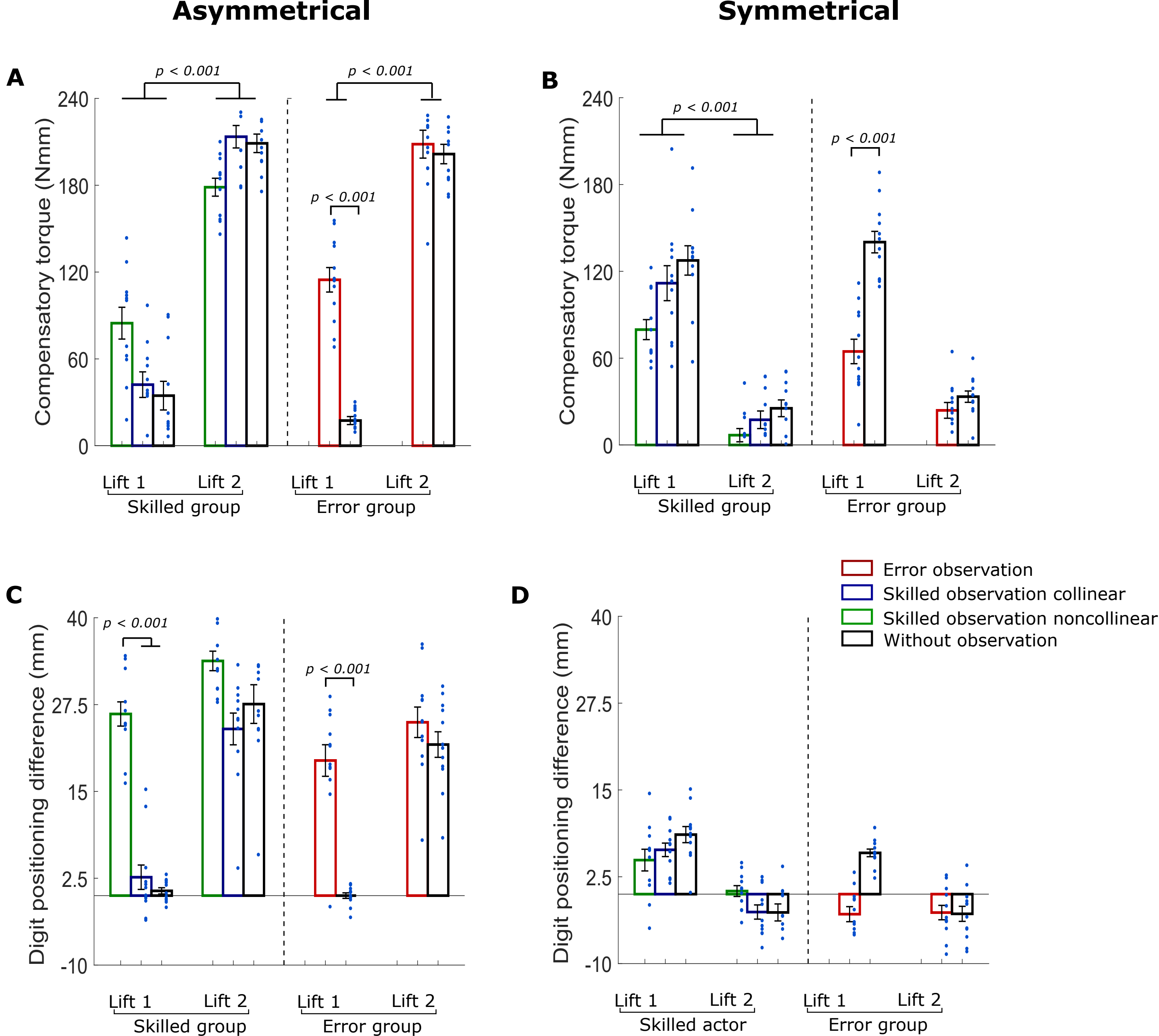


A
140
192
20
200
48
45
53
B
Roll
X
Z
Y
-
+
Thumb
Index finger
T_{comp}
+
T_{comp}
-
L
C
R
C
Actor
Participant


A
Compensatory torque (Nmm)
400
300
200
100
0
0
500
1000
1500
2000
Time (ms)
B
Digit positioning difference (mm)
50
37.5
25
12.5
0
0
500
1000
1500
2000
Time (ms)
C
Total GF (N)
30
22.5
15
7.5
0
0
500
1000
1500
2000
Time (ms)
D
LF difference (N)
10
7
4
1
-2
0
500
1000
1500
2000
Time (ms)
Naïve lift
Skilled collinear
Skilled noncollinear



A
Compensatory torque (Nmm)
320
240
160
80
0
p < 0.001
Old sym
New asym
Old sym
New asym
Informed actor
Blind actors
B
Digit positioning difference (mm)
60
40
20
0
-20
p < 0.001
Old sym
New asym
Old sym
New asym
Informed actor
Blind actors
C
Total grip force (N)
32
24
16
8
0
p = 0.02
p = 0.02
Old sym
New asym
Old sym
New asym
Informed actor
Blind actors
D
Load force difference (N)
10
5
0
-5
-10
p < 0.001
p < 0.001
p = 0.04
Old sym
New asym
Old sym
New asym
Informed actor
Blind actors
Naïve lift
Informed collinear lift
Informed noncollinear lift



Asymmetrical
Symmetrical
A
B
C
D
p < 0.001
Compensatory torque (Nmm)
240
180
120
60
0
Lift 1
Lift 2
Skilled group
Error group
Digit positioning difference (mm)
40
27.5
15
2.5
-10
Skilled actor
Error observation
Skilled observation collinear
Skilled observation noncollinear
Without observation