Bimanual lifting: Do fingertip forces work independently or interactively?

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Abstract

Bimanual coordination is a commonplace activity, but the consequences of using both hands simultaneously are not well understood. Here, we examined fingertip forces across four experiments where participants undertook a range of bimanual tasks. We first measured fingertip forces during simultaneous lifts of two identical objects, noting that individuals held the objects with more force bimanually than unimanually. We then varied the mass of the objects held by each hand, noting that when both hands lifted together performance was equivalent to unimanual lifts. We next measured one hand's static grip force while the other hand lifted an object. Here, we found a gradual reduction of grip force throughout the trial, but once again no evidence of one hand influencing the other. In the final experiment we tested whether tapping with one hand could influence the static holding force of its counterpart. Although we found no changes in holding force as a direct consequence of the other hand's actions, we found clear differences from one task to the other, suggesting an effect of task instruction. Overall, these results suggest that fingertip forces are largely independent between hands in a bimanual lifting context, but are sensitive to different task demands.

Keywords :
Bimanual coordination, grip force, bimanual coupling, grasping

Introduction

We more often than not use both our hands to perform common tasks. Usually some of these tasks require different actions for each hand, yet we are still successful in coordinating both our hands to act simultaneously, facilitating our performance towards the end result. However, while they seem to act smoothly in such cases, there are factors that can influence their performance.

When we reach and point at targets bimanually, the hands exhibit a degree of temporal synchrony. For example, even if both hands are making reaches of different amplitudes, they both appear to start and end their movements simultaneously to the common observer. These findings have been replicated in a wide range of different contexts to date (Fowler, Duck, Mosher, & Mathieson, 1991; Jackson, Jackson, & Kritikos, 1999; Marteniuk, MacKenzie, & Baba, 1984; Sherwood, 1994). Recent work examining bimanual reaching showed asynchronous movement onset and movement end times when the targets were located at different distances from the body (Riek et al., 2003). Additionally, in the spatial domain, short movements were on average overshot when the other hand performed a long reach, and long movements were undershot when the other hand performed a short one, when compared with the control condition were both hands reached for targets of same distance (see also Spijkers and Heuer 1995).

To examine bimanual temporal asymmetries between hands, Buckingham et al (2010) had participants perform contralateral unimanual reaches, and equivalent bimanual reaching with an ipsilateral-reaching counterpart. In their task, the right hand reached toward targets at different distances in the right side of space while simultaneously the left hand reached at a fixed target on the right space (Buckingham, Binsted, & Carey, 2010). The left hand's contralateral reach showed decreased movement times (MTs) when the right hand performed a concurrent reach into ipsilateral space, compared to when reaching alone. The opposite configuration – right hand reaching in contralateral space with the left hand performing a concurrent ipsilateral reach – showed no differences in MTs when compared to the unimanual condition. The authors noted that the left hand's performance was improved when the right hand was present, and provided support to the notion that the left hand is yoked to the right. A number of studies have demonstrated, that bimanual reaching-to-point performance is subject to asymmetries, both in the spatial and the temporal domain (Fowler et al., 1991; Koeneke, Lutz, Wüstenberg, & Jäncke, 2004; Marteniuk et al., 1984; Marteniuk, Leavitt, MacKenzie, & Athenes, 1990), in contrast to the original notion that bimanual movements begin and end their movements in perfect synchrony (Kelso et al., 1979).

A series of experiments investigating hand trajectories while participants reached for targets, examined this phenomenon and how it manifests spatially (Kelso, Putnam, & Goodman, 1983). The authors placed an obstacle between one hand and its target and during a bimanual reach toward target pairs, and observed that for some participants, the unobstructed hand made a slight (unnecessary) vertical elevation in space, presumably caused by the hand reaching over the obstacle. In a more recent study, participants reached toward visual targets with unimanual and bimanual reaches while one of the targets was displaced mid-trial (Diedrichsen, Nambisan, Kennerley & Ivry, 2004). The hand moving to the displaced target corrected its trajectory, but in almost all cases the hand moving to the stationary target performed a minor yet significant perturbation of its trajectory in the same direction as the other hand. The authors ruled out any biomechanical factors through additional kinematic measures and suggested a modulation of the motor command issued to the hand moving towards the stationary target. Most importantly, collective evidence suggests that task demands play a major role in how temporal and spatial coupling is manifested during bimanual coordination.

Although spatial coupling between hands happens in a lot of cases during bimanual reach-to-point tasks, it is less clear whether this coupling may also be present in the grasping system. Typically when grasping an object, participants will adjust the distance between their thumb and index finger slightly wider than the distance of the planned contact points on target objects, and always in proportion to an object's size (Jeannerod, 1984). It has been shown that bimanual reach-to-grasping tasks cause a reduction in peak velocities and an increase in MTs of the reaching phase, in addition to wider peak grip apertures (PGA) of both hands compared to unimanual tasks (Jackson, Jackson & Kritikos, 1999). The authors noted that each hand independently scaled grip aperture to the size of the target object. In other words, even though the parameters of the reach were synchronised, the grip aperture profiles were appeared independent during a bimanual reach, providing evidence that the grip aperture is parameterised independently for each hand. They have demonstrated, however, a slight cost of bimanual grasping, shown by a proportional increase of PGA of both hands in a bimanual condition when compared to equivalent unimanual grasps. This effect could be ascribed to an increase in task difficulty rather than to an influence of one hand over the other, as there was no bimanual asymmetry, namely yoking, between PGAs. Recently, a study demonstrated that when participants reached, grasped, and transported cylinders of either congruent/incongruent sizes or congruent/incongruent target locations, they showed spatial coupling for congruent conditions and independent upper limb performance for incongruent conditions (Mason & Bruyn, 2009). Specifically, some temporal coupling was observed for the transport component, while spatial measures of the grasping component, such as PGA, suggested a low degree of spatial coupling in both congruent and incongruent conditions. They speculated that coupling may be present in situations where it can facilitate performance such when both hands act on the same parameters under a shared command, and not present when it can hinder performance, e.g. when each hand requires a specific set of commands for its respective task's parameters. At this point, it is important to clarify the distinction between reach-to-point and reach-to-grasp tasks. While the reaching component's neural substrate activation overlaps the grasping component's (Filimon, 2010), there do appear to be networks which code for one task but not the other. Specifically, grasping shows a higher degree of activation when compared to a pointing task (Pierno et al., 2009). For example, the anterior intraparietal sulcus (aIPS) shows activation in reach-to-grasp tasks, and is also activated in grasping tasks that lack the reaching component. Additionally, the superior parietal lobule (SPL) shows overlapping activation during grasping and in reaching tasks (Castiello, 2005), but a higher degree of activation in those grasp related areas when compared to a reaching-to-point task (Cavina-Pratesi et al., 2010). This distinction was also shown behaviorally earlier, in a reaching-to-point versus reaching-to-grasp study (Carnahan, Goodale, & Marteniuk, 1993). In one of the conditions the targets were perturbed during the trial, forcing an online reach correction to localize the target. The parameters of the reach ('peak velocity' and 'time to peak velocity') were different when pointing than they were when reaching to grasp. We find this distinction strong enough to bridge the analogy between fingertip forces in reach-to-grasp tasks and arm kinematics in reach-to-point tasks.

Typically, upon contact with an object, the forces that have to be coordinated for a successful lift are grip force (GF) – the force that is exerted between the index finger and thumb – and load force (LF) – the force that is required to overcome gravity. GF is always increased prior to LF increases, with the latter reflecting the mass of a given object, and GF increases as friction is reduced (Johansson & Westling, 1984). The ratio between GF and LF is kept constant when the lifted object is being transported in different directions, or when additional weight is being added to it (Flanagan & Wing, 1997). Anticipation of the object's weight is driven by the predicted weight of the objects (Johansson & Westling, 1988) based on its size (Gordon, Forssberg, Johansson, & Westling, 1991a, 1991b) and identity (Gordon, Westling, Cole, & Johansson, 1993).

To date, no studies have examined how individuals coordinate their fingertip forces when lifting objects with both hands simultaneously. The closest relevant study which has investigated grip force control in the context of unimanual object lifting found no asymmetries in either sensorimotor prediction or fingertip force adaptation between the dominant and non-dominant hands. (Buckingham, Ranger, & Goodale, 2012). The goal of the current work was to examine (1) whether fingertip forces are parameterised independently for each hand, and (2) whether the fingertip forces of one hand can be influenced by the other hand. To this end, we examined various grip and load force parameters in a bimanual context and compared them to equivalent unimanual lifts. In the first experiment we examined whether one hand's grasping and lifting performance was influenced by the other hand performing the same task. In the second experiment, we examined whether lifting different weights with each hand would reveal yoking between the hands in the force parameters. In the third experiment we examined whether a hand which was already holding an object could have its static holding force influenced by the other hand's lift. Finally, in the fourth experiment, we examined how one hand's static holding force could be influenced by its counterpart performing a range of non-lifting motor tasks, such as tapping or typing on a keyboard.

Experiment 1

Methods

Participants

A total of 18 self-reported right-handed individuals (mean age 23.6 years, SD=4.7, range=19-35) were recruited at the Heriot-Watt University, Edinburgh, comprising of 7 males and 11 females. All participants had normal or corrected-to-normal vision and no motor impairments. All participants gave informed consent prior to testing, and all procedures were approved by the local ethics board.

Stimuli and procedure

A custom written script in MATLAB (Mathworks) controlled the trial start and end cues with a short “beep”, and handled the data collection from a pair of force sensors (Nano17, ATI Tech). A pair of PLATO shutter goggles (Translucent Technologies) were used to allow participants’ vision only for the duration of each trial, which lasted for 4 seconds. The shutter goggles ensured that the participants would not witness the experimenter moving the objects around between trials, to avoid being influenced by the apparent weight and hand kinematics, and to standardize the object’s exposure duration. The stimuli were two identical black plastic cylinders of equal mass (400 grams) and equal volume (7.5 cm diameter, 7.5 cm tall), placed on noise-dampening green felt pads. The force sensors were mounted on top of each stimulus attached to a custom made handle (Figure 1).

INSERT FIGURE 1 ABOUT HERE

Participants sat on a chair in front of a large table and placed their hands on it in a relaxed manner, barely touching a plastic button attached to the edge with their index fingers, palm resting on the table. The button served as a start and end point for each trial. Stimuli were placed symmetrically the same distance from each hand (50 cm), along the midline of the body, 25 cm apart laterally (Figure 2). The participants were instructed to lift, without delay, whatever object was on the two felt pads; specifically, lift with their left hand if the left cylinder was present, with their right if the right was present, or with both hands if both cylinders were present. After the auditory cue, the goggles cleared and participants reached toward and lifted the stimuli to a marked height (approximately 23 cm), and held them steady until the second beep sounded and then returned the objects to the table surface. Participants were instructed to lift the object(s) by grasping the handle on top of the object with their thumb and index finger formulating a ‘precision grip’. This grip was practiced with a few trials before the start of the experiment for the subject to become familiarised with the technique. The goggles then closed and obscured the participant’s vision, at which point they placed the objects back to the felt pads. Each session featured 60 trials (20 Left hand, 20 Right hand, 20 Bimanual). Trials were presented in one of four random orders, and the experiment took approximately 20 minutes.

Sensors recorded 3D forces at 1000 Hz, and the data were smoothed with a low-pass Butterworth filter with a cut-off frequency of 14 Hz. The forces orthogonal to the surface of the grip pads (Z-axis) were defined as grip force (GF) and the remaining forces (X and Y-axes) were vector summed to yield load force (LF). These force vectors were differentiated with a 5-point central difference equation to yield grip force rate (GFR) and load force rate (LFR), the main indices of sensorimotor prediction, as they are variables that are measured at the earliest point of a lift. Then, we calculated the mean GF during the holding phase, which was defined as the average GF between 2.5 to 3.5 seconds of each 4-second trial. We chose this particular time interval based on observations that, on each trial, all participants had completed the lift and the object was being held static above the table surface (i.e., with no large deviations in load force). Additionally, in order to confirm the synchronicity of the lifts, we first identified lifting onset as the timepoint at which LF was larger than 0.1 N for each hand. To determine whether lifting occurred synchronously we then subtracted the left hand's load force onset value from the right hand's and the resulting difference between hands was tested with a one-sample t-test against zero. The rest of the dependent variables (LFR and holding GF) were analyzed with a 2×2 repeated measure ANOVA with the factors of Hand (Left, Right) and Condition (Unimanual, Bimanual). Throughout, when Mauchley's test of sphericity showed a violation of sphericity, Greenhouse-Geisser corrections were used. Error bars show the normalized error of the mean, a process that involves normalizing individual data by removing between-subject variance (Cousineau, 2005).

INSERT FIGURE 2 ABOUT HERE

Results

Peak grip force rate

There were no differences between Condition (F(1, 17) = 0.46, p = .51, η_p^2 = .02); Figure 3A) or between Hand (F(1, 17) = 0.34, p = .57, η_p^2 = .01), and no interaction between Condition and Hand (F(1, 17) = 3.25, p = .09, η_p^2 = .16).

Peak load force rate

There was no difference in the rate of load force between hands (F(1,17) = 0.61, p = .44, η_p^2 = .03; Figure 3B), but LFR was significantly higher in the unimanual condition compared to the bimanual condition (F(1, 17) = 5.25, p = .03, η_p^2 = .24; M = 36.18 vs. 34.88). There was no interaction between Condition and Hand (F(1, 17) = 0.002, p = .96, η_p^2 < .01).

Holding grip force

We found that bimanual holding GF was larger than unimanual holding GF (M = 6.31 vs. 5.98; F(1, 17) = 6.64, p = .02, η_p^2 = .28). There were, however, no differences between Hand (F(1, 17) = 0.24, p = .62, η_p^2 = .01; Figure 3C) and no interaction between Hand and Condition (F(1, 17) = 1.41, p = .25, η_p^2 = .07).

Load force onset

When comparing the temporal LF onset difference between hands in the bimanual condition (M = -13.3, SD = 21.9) against zero, we found no significant difference (t(18) = -0.017, p = .35) suggesting that both hands begun the process of lifting simultaneously.

INSERT FIGURE 3 ABOUT HERE

Discussion

In this experiment, we set out to examine fingertip force control during a bimanual task when force demands were identical between hands. There was no difference in LF onset, indicating that both hands initiated their respective lifts simultaneously. In terms of force parameters, we found that when participants lifted identical objects bimanually, the pre-liftoff peak grip force rates of the left hand did not differ from those of the right hand. However, participants tended to hold the objects with more force when grasping in a bimanual context than they did in equivalent unimanual lifts. Furthermore, we did find that bimanual peak load force rate was lower when compared to the equivalent unimanual lifts. We propose that both of these differences reflect a novel cost associated with bimanual lifting, akin to the preparation and movement time “bimanual cost” by Ohtsuki, (1994; cf. Blinch, Franks, Carpenter, & Chua, 2015). Although novel, a bimanual cost to force production is not surprising, and might reflect a safety margin associated with the attentional demands of concurrent object lifting. Next, to directly examine whether there is any evidence of bimanual force yoking, we examined how individuals control their fingertip forces when lifting objects of a different weight with each hand. A design that offers an analogous situation with that of asymmetrical targets may offer additional insights in fingertip force parameterisation between hands and bimanual conditions. We would expect that the hand lifting the heavy object would undercompensate its force application and the hand lifting the light one would overcompensate when these objects are both lifted bimanually.

Experiment 2

Methods

Participants

A total of 21 self-reported right-handed individuals (mean age 24.3 years, SD = 5.3, range = 19-36) were recruited at the Heriot-Watt University, Edinburgh, comprising of 8 males and 13 females. All participants had normal or corrected-to-normal vision and no motor impairments. Two participants took part in Experiment 1. All participants gave informed consent prior to testing, and all procedures were approved by the local ethics board.

Stimuli and procedure

The apparatus and procedures were identical to Experiment 1, with the exception that the stimuli, which were still identical-looking black cylinders of equal size (7.5 cm diameter, 7.5 cm tall), but could weigh either 200-g or 400-g, and the force data was recorded at 500Hz. Each participant lifted the six hand/mass configurations (10 Left - Light mass, 10 Right - Light mass, 10 Left – Heavy mass, 10 Right – Heavy mass, 10 Bimanual Heavy – Light, 10 Bimanual Light - Heavy) in one of four random orders, for a total of 60 trials.
Dependent variables were analyzed with 2×2×2 repeated measure ANOVAs, Condition (Unimanual, Bimanual), Mass (Light, Heavy), and Hand (Left, Right).

Results

Peak grip force rate

We found no main effect of Condition (F(1, 20)= 1.8, p = .19, η_p^2 = .08), Mass (F(1, 20) = 0.5, p = .46, η_p^2 = .02), or Hand (F(1, 20) = 2.44, p = .13, η_p^2 = .11; Figure 4A). There was, however, a significant interaction between Condition and Hand (F(1, 20) = 7.04, p = .015, η_p^2 = .26), although non interaction was observed between Condition and Mass (F(1, 20) = 0.02, p = .87, η_p^2 < .01), Hand and Mass (F(1, 20) = 0.28, p = .6, η_p^2 = .01), or Condition and Hand and Mass (F(1, 20) = 0.13, p = .71, η_p^2 < .01).

Peak load force rate

In contrast of grip force rate, peak load force rate showed a main effect of Mass (F(1, 20) = 12.45, p = .002, η_p^2 = .38; Figure 4B). This is likely because the objects weighed different amounts from one another, and load force parameters are more closely linked to object mass than grip force parameters. As with grip force rate, we found no effect of Hand (F(1, 20) = 3.26, p = .09, η_p^2 = .14) or Condition (F(1, 20) = 4.25, p = .053, η_p^2 = .17). No interaction was found between Hand and Mass (F(1, 20) = 0.04, p = .84, η_p^2 < .01), Hand and Condition (F(1, 20) = 1.63, p = .22, η_p^2 = .07), Mass and Condition (F(1, 20) = 1.29, p = .27, η_p^2 = .06), or Hand and Mass and Condition (F(1, 20) = .06, p = .81, η_p^2 < .01).

Holding grip force

In terms of holding forces, participants gripped the heavy object with more force than they used to hold the light one (5.43 vs. 4.12; F(1, 20) = 84.84, p < .001, η_p^2 = .81; Figure 4C). However, there was no difference between the bimanual and unimanual conditions (F(1, 20) = 0.12, p = .72, η_p^2 < .01), nor between Hand (F(1, 20) = .002, p = .96, η_p^2 < .01). There were no interactions between Condition and Mass (F(1, 20) = 0.88, p = .36, η_p^2 = .04), Condition and Hand (F(1, 20) = 1.98, p = .17, η_p^2 = .09), Hand and Mass (F(1, 20) = 1.04, p = .32, η_p^2 = .05), or Condition and Hand and Mass (F(1, 20) = 1.1, p = .3, η_p^2 = .05).

Load force onset

Comparing the LF onset differences between object configurations against zero in the bimanual conditions, we found that the light object was lifted before the heavy object, such that in the Light-Heavy object configuration the left hand lifted earlier than the right hand (M = -43.51 ms, SD = 48.87; t(20) = -4.08, p < .001) and the Heavy-Light object configuration the right hand lifted earlier than the left hand (M = 32.57 ms, SD = 52.14; t(20) = 2.86, p = .01).

INSERT FIGURE 4 ABOUT HERE

Discussion

In this experiment we examined how participants controlled their grip forces when lifting differently-weighted objects with either hand concurrently. We found no evidence of overflow in these contexts – higher forces were used to lift heavier objects regardless of condition, and the effect of object mass did not differ between the bimanual and unimanual lifts. Additionally, the light object was lifted before the heavy one regardless of mass configuration. This type of temporal un-coupling was not expected, in fact we expected both hands to begin the lift simultaneously, similarly to Experiment 1. In contrast, there was no bimanual force cost observed between conditions, as it was strongly seen in Experiment 1. Indeed, the lack of bimanual cost might be related to the lack of coupling in this second experiment – potentially both due to the asymmetrical task demands causing the fingertip forces between hands may become decoupled. This phenomenon could arise in situations where the tasks demands are such to ensure that any deviation from the required action due to extraneous coupling/costs may be particularly detrimental to the task success. These results suggest that fingertip forces are parameterised independently for each hand, pronounced when lifting disparate weights. Participants used grip forces similar to those used when each hand lifted in isolation regardless of the different mass in the other hand. However, that investigation was limited in regards to the situation, in which both hands had already lifted and optimized a stable hold. In such a situation, independent application of holding grip force might have been more easily achieved through time, thus not clearly investigating potential transient effects. To more directly investigate the degree to which one hand influences the other hand’s fingertip forces, we next examined how a hand which is already holding an object in a stable manner reacts to a lift of another object by its counterpart. With this design, we will be able to observe an optimized holding grip force application and expect a degree of interference from the other hand performing a lift.

Experiment 3

Methods

Participants

A total of 24 self-reported right-handed individuals (mean age 22.1 years, SD = 2.4, range = 19-28) were recruited at the Heriot-Watt University, Edinburgh, comprising of 10 males and 14 females. All participants had normal or corrected-to-normal vision and no motor impairments. All participants gave informed consent prior to testing, and all procedures were approved by the local ethics board.

Stimuli and procedure

The stimuli and setup were identical to Experiment 2. Participants lifted one object with one hand (precision grip) at the sound of the cue and held the object in a stable manner at a height of 23cm (indicated by a height marker next to the stimuli) for the duration of the trial (7 seconds). Four (4) seconds after the first sound cue, another cue sounded and participants reached and lifted the second object with their other hand at the same height while still

holding the first object, and held it in a stable manner for the rest of the trial. Seven (7) seconds after the first cue, the final cue sounded and they returned both objects on the felt pads. Participants were allocated into two groups by alternating participant number. The first group lifted the first object (the holding hand's object) with their right hand and lifted the second object (the lifting hand's object) with their left. Participants in the second group used their left hand for holding and their right for lifting. Each participant performed 60 randomized trials, 20 for each mass configuration (20 Left - Light mass, Right – Heavy mass, 20 Right - Light mass, Left – Heavy mass, 20 Left – Light mass, 20 Right – Light mass). In each trial, the holding hand's grip force was segregated into 3 distinct timed events: Unimanual holding (0.5 a second duration, from second 2.5 to 3), During other hand's lift (from the point where the grip force of the lifting hand exceeded 0.1 Newtons and for 0.5 seconds), and Bimanual holding (0.5 seconds duration, from second 5.5 to 6) (Figure 5). The 0.5 second window was selected for all three grip force events because that was the average lifting duration of the lifting (second) hand. To directly examine the effect of the lifting hand's mass on the holding hand, we examined holding force only in the conditions where the holding hand's mass was constant; Equal (both hands lifted 200gr), and Lighter (holding hand 200gr, lifting hand 400gr). In simpler terms, we removed the level of the Mass factor where the holding hand lifted the heavier, 400gr, object.
The dependent variable was analyzed with a 3×2×2 mixed ANOVAs, with factors of Event (Unimanual holding, During other hand's lift, Bimanual holding) and Mass (equal, lighter) as within-group, and Holding hand (Left, Right) as a between-groups factor.

INSERT FIGURE 5 ABOUT HERE

Results

Holding grip force

We found no effect of Mass (F(1, 11) = 1.01, p = .33, η_p^2 = .08) or Holding hand (F(1, 11) = 0.26, p = .61, η_p^2 = .02), but an effect of Event was observed (F(1.21, 13.33) = 6, p = .02, η_p^2 = .35; Figure 6). No interaction was found between Event and Mass (F(2, 22) = 2.74, p = .09, η_p^2 = .2), Event and Holding hand (F(2, 22) = 0.2, p = .81, η_p^2 = .02), Holding hand and Mass (F(1, 11) = 0.28, p = .61, η_p^2 = .02), or Event and Holding hand and Mass (F(1.23, 13.61) = 1.31, p = .28, η_p^2 = .1).

INSERT FIGURE 6 ABOUT HERE

Discussion

In this experiment we set out to examine any potential influence of lifting an object of equal or different mass to the other hand's object, while the other hand was already holding a similar object in a stable manner. We found that the mass being lifted by the other hand had no obvious effect on the holding hand's grip force, instead observing a consistent reduction of holding grip force as the trial unfolded. That is, holding hand's grip force was lower during the other hand's lift compared to when it was holding an object in a unimanual context, and was further reduced when both hands were holding their objects in a stable manner. Still our results show no overflow of forces from one hand to the other at any point during lifting or holding an object of either identical or different mass. The logical step is to understand if this lack of fingertip force influence between hands is limited only to bimanual lifting. There is evidence that suggests that tapping bimanually requires increased attention and motor coordination (Peters, 1985). This is a type of cognitively demanding task that is unrelated to lifting. To conclude this series of examinations on the influence of one hand's fingertip forces on the other, we undertook a final experiment testing whether performing an ordinary task such as tapping or typing with one hand could influence the holding grip force of the other hand that was holding the same object used in the previous experiments. If we assume that the type of task is a key factor in holding grip force independent parameterisation, then we are expecting a degree of force overflow on the holding hand from the other, tapping or typing hand.

Experiment 4

Methods

Participants

A total of 20 self-reported right-handed individuals (mean age 22 years, SD = 1.9, range = 19-26) were recruited at the Heriot-Watt University, Edinburgh, comprising of 7 males and 13 females. All participants had normal or corrected-to-normal vision and no motor impairments. All participants gave informed consent prior to testing, and all procedures were approved by the local ethics board.

Stimuli and procedure

Similar to Experiment 1, the same 400g black cylinder (7.5 cm diameter, 7.5 cm tall) was always placed on the right side of the participant. Force data were recorded at 500Hz. On the left side of the participant, symmetrically opposite to the cylinder, a white round felt marker was placed. A wireless keyboard was placed beside the white mark (Figure 7). The participants went through four counterbalanced blocks of trials, one for each condition. All trials consisted of two distinct sections separated by a sound cue. In the first section, starting with a sound cue, the participant lifted the cylinder with their right hand and held it in a stable manner at a height of 23cm indicated by the height indicator next to the cylinder, and placed their left hand's index finger in a pointing fashion on the white marker. This section lasted for 3 seconds, and was the same for all participants and all conditions. On the 3rd second, another cue sounded and the second section began. That section depended on the condition that was pre-instructed before the start of each block, and it always lasted for 4 additional seconds (7 seconds total per trial). On the Control condition, participants were instructed to remain as they were at the end of the first section of the trial, holding the object with their right hand and keeping their left hand's index finger on the white marker. On the Tapping Rhythm condition, a metronome click played for 4 seconds (90bpm) and they were instructed to tap with their left hand's index finger on the white marker, matching the tempo. On the Tapping Fast condition, they were instructed to tap "as fast as possible" with their left hand's index on the white marker (no metronome). The last condition was Typing, and they were instructed to type with their left hand the word "saw" once on the keyboard and return to the white marker. The holding grip force windows selected for comparison were of half a second duration (500ms) each. Specifically, averaged holding grip force of seconds 2.5 to 3rd second (when right hand's object was stable and left hand idle) and seconds 5.5 to 6th (midpoint of the left hand's task execution), "unimanual holding" and "during other hand's task" respectively.

The mean grip force of the holding hand was analyzed with a 2×4 repeated-measures ANOVA with factors of Event (Unimanual holding, During other hand's task) and Condition (Control, Tapping Fast, Tapping Rhythm, Typing).

INSERT FIGURE 7 ABOUT HERE

Results

Holding grip force

There was a significant effect of Condition ($F(3, 57) = 5.43$, $p = .004$, $\eta_p^2 = .21$; Figure 8), but not an effect of Event ($F(1, 19) = 0.54$, $p = .47$, $\eta_p^2 = .03$). Pairwise comparisons showed that participants held the object with more force during the Tapping Fast condition than during Control ($M = 6.17$ vs. 5.38; $p < .001$) and more force during Tapping Rhythm than they did during Control ($M = 6.12$ vs. 5.38; $p = .02$). Control did not differ from Typing ($p = .89$), Tapping Fast did not differ from Tapping Rhythm ($p = 1$) nor from Typing ($p = .84$), and neither did Tapping Rhythm from Typing ($p = 1$). Critically, however, there was no significant interaction between Condition and Event ($F(3, 57) = 0.24$, $p = .87$, $\eta_p^2 = .01$).

INSERT FIGURE 8 ABOUT HERE

Discussion

In this experiment we examined if an otherwise stable holding hand can be influenced by the other hand performing an ordinary task. We found that, when it’s counterpart was performing a different task, the holding hand held with more force than when the other hand was resting. However, as these differences were also observed in the holding hand before the other hand initiated its task, this excess force is unlikely to be a consequence of the task itself. Indeed, the lack of interaction between Event and Condition indicates that the effect of condition is not due to the performance of the other hand, but instead a consequence of task set (i.e., instruction and/or task anticipation).

General Discussion

This series of experiments aimed to investigate how actions undertaken by the other hand that could influence fingertip forces when lifting and holding an object. In Experiment 1 we examined whether lifting two identical objects bimanually would differ from when lifting these objects with one hand in isolation. We found that lifting with one hand or both hands had no impact on the task in terms of sensorimotor prediction, with equivalent levels of peak grip force rate prior to liftoff. We did, however, find that both hands applied additional holding force in the bimanual condition compared to the unimanual condition. This increase of ~0.3N might reflect a bimanual cost in holding force – to our knowledge the first description of such an effect. Next, to examine if there was any evidence of overflow between the hands, we examined simultaneous lifts of objects with different masses, compared to unimanual equivalents. Our results suggested that when there was a different mass in each hand, sensorimotor prediction was still unaffected in a bimanual context; unimanual grip force rate and holding force did not differ from bimanual grip force rate and holding force. It is important to mention that the lack of a bimanual cost in Experiment 2, in contrast to Experiment 1, was surprising and unexpected. This finding is not consistent with the reach-to-point literature where asymmetrical movements introduce an increased bimanual cost (Blinch et al., 2015; Spijkers, Heuer, Kleinsorge, & van der Loo, 1997). To add to this, there was no temporal coupling as expected, but each hand started lifting the lighter object first. In Experiment 3 we examined how holding grip force of one hand was modulated while the other hand started lifting an object. The different masses of the lifting hand’s objects did not contribute to any changes in the holding hand’s grip force. To conclude this series of studies, in Experiment 4, we examined how holding grip force was influenced when the other hand was performing a range of tapping tasks. Comparing the holding hand’s grip force before and during the other hand’s tasks, we found no changes in holding force. However, holding force was significantly increased in the tapping conditions compared to unimanual conditions, regardless of the other hand’s involvement in the task.

Overall, this series of experiments suggests that the fingertip forces of each hand are independently scaled for each object of different mass, that is, fingertip forces of one hand were not influenced by those of the other. These results are consistent with how individuals coordinate their grip scaling in reach-to-grasp studies (Jackson et al., 1999; Mason & Bruyn,

2009) on the question of hand yoking. Our findings suggest that there is no apparent yoking of forces between hands in a bimanual context. However, in the Jackson et al. study when participants were reaching to grasp objects bimanually, while independently scaling their aperture to the size of each target object, there was an increase of both peak grip apertures regardless of grasping context – a bimanual cost in terms of grip aperture scaling. In our study, we observed a similar bimanual cost of mean holding force when holding bimanually compared to when holding unimanually when objects were of the same mass, but not when their mass differed in experiment 2. In experiment 2, fingertip forces were not coupled as each hand's force performance was identical to its unimanual equivalent. This lack of a bimanual force cost in experiment 2 was an unexpected finding. One possibility is that this bimanual cost failed to arise due to the asymmetrical task demands in the second experiment. Our findings in the first two experiments suggest that the reach-to-grasp system differs from the reach-to-point system in that the model of neural crosstalk does not apply. We speculate that this distinction may be, in part, due to the accuracy demands, and thus speed, of each type of movement. The term 'speed' is used in this context to describe processing and motor execution of a motor command rather than an implicit task requirement issued to a participant. Reach-to-point motions are predominantly fast movements with a clear arm flexing action that terminates at the moment of target contact, while a reach-to-grasp execution involves a more complex set of commands that include the grasping component. It is proposed that the distal muscles involved in grasping and lifting behave differently to the proximal muscle groups of the shoulder/arm typically used to reach and point (Dohle, Ostermann, Hefter, & Freund, 2000). In situations where speed is crucial for the successful execution of a task, such as reach-to-point experiments, bimanual coupling may be beneficial due to reduced degrees of freedom in movement parameterization (Temprado et al. 1997). Interacting with objects, as opposed to manual localization tasks, usually involves slower actions due to the tasks demands (grip aperture modulation, coordinating grip and load forces during liftoff, maintenance of forces). Situations where a task requires slower movements serves as a good example of the suggestion posed by Mason and Bruyn (2009) that, in situations where coupling is not beneficial it does not occur, and each hand's action is parametrized separately. The issue of speed may be the case with the collective evidence of the older studies on bimanual coordination using reach-to-point paradigms, and why these asymmetries are not present in the recent reach-to-grasp paradigms; the grip/lift system may behave in a similar fashion as the reach-to-grasp, since both require slower actions. Similarly, in Experiment 3 there was no increase of holding hand's force when the other hand lifted a heavier object, an observation that suggests no yoking of forces in any part of the lifting phase. It appears that fingertip forces of one hand were only slightly affected by the other hand performing a lift, and that reduction may have been a general tendency to optimize holding force as time progressed, regardless of the difference in force demands between hands. In Experiment 4, we expected an increase of force during the various Tap conditions, but this increase was evident even before the other hand had started tapping, suggesting that the increase was not caused by the action per se. We can only speculate that this increase in holding force was a consequence of task preparation. It may have been that prior knowledge of the type of task participants would have been required to perform with the other hand primed the sensorimotor system to preconfigure fingertip forces to include an extra safety margin for the holding hand to maintain its grasp successfully.

To sum up, this series of studies has shown that overflow between the fingertip forces of each hand is not apparent in the same fashion as broader bimanual coordination involving tasks that require rapid reaching movements. In contrast to manual localization literature, fingertip force scaling appeared to operate independently; individuals are able to lift objects with both hands just as successfully as they can lift one object with one hand. There was a degree of force overcompensation when both hands were required to apply identical forces, which could be interpreted as a bimanual cost in this simple situation, a phenomenon not seen when required forces differed between the hands. Similarly, fingertip forces when holding an object were not affected by overflow from the other hand's actions whether those were related or unrelated to object lifting. It appears that both hands operate independently from one another in terms of fingertip force control and parameterization, but show compensatory mechanisms under certain conditions. Most interesting is that those conditions seem to be working in the opposite direction than reaching-to-points tasks. Bimanual cost increases as asymmetries between hands increase when reaching-to-points, and is abolished when asymmetries are introduced in object lifting.

Figure captions

Figure 1. Image showing the [A] force sensor attached on a [B] custom-made handle, that is mounted on one of the stimuli

Figure 2. Schematic of the experimental setup of the table surface from the participant's perspective

Figure 3. The means of [A] peak GFR, [B] peak LFR, and [C] holding GF values for each hand across conditions. Error bars show the normalised standard error of the mean. N.B. as no significant differences were observed in [A], this portion of the figure is for descriptive purposes only.

Figure 4. The means of [A] peak GFR, [B] peak LFR, and [C] holding GF values for each hand across conditions. Error bars show the normalised standard error of the mean

Figure 5. Example trial of the holding hand's grip force profile across time, and how each grip force event was segregated

Figure 6. The mean holding GF values for each mass configuration. Equal – when holding hand was hefting an object of equal mass to the lifting hand (both 200gr), and Lighter – when lifting hand was lifting a heavier object (400gr) to the holding hand. Left and Right describe the holding hand. Three conditions represent the Unimanual holding (only holding hand), During other hand's lift (the time period when the other hand was lifting), and Bimanual holding (when both hands were holding their respective objects). Error bars show the normalised standard error of the mean

Figure 7. Schematic of the experimental setup of the table surface from the participant's perspective

Figure 8. The mean holding GF values for each event within every condition. Error bars show the normalised standard error of the mean

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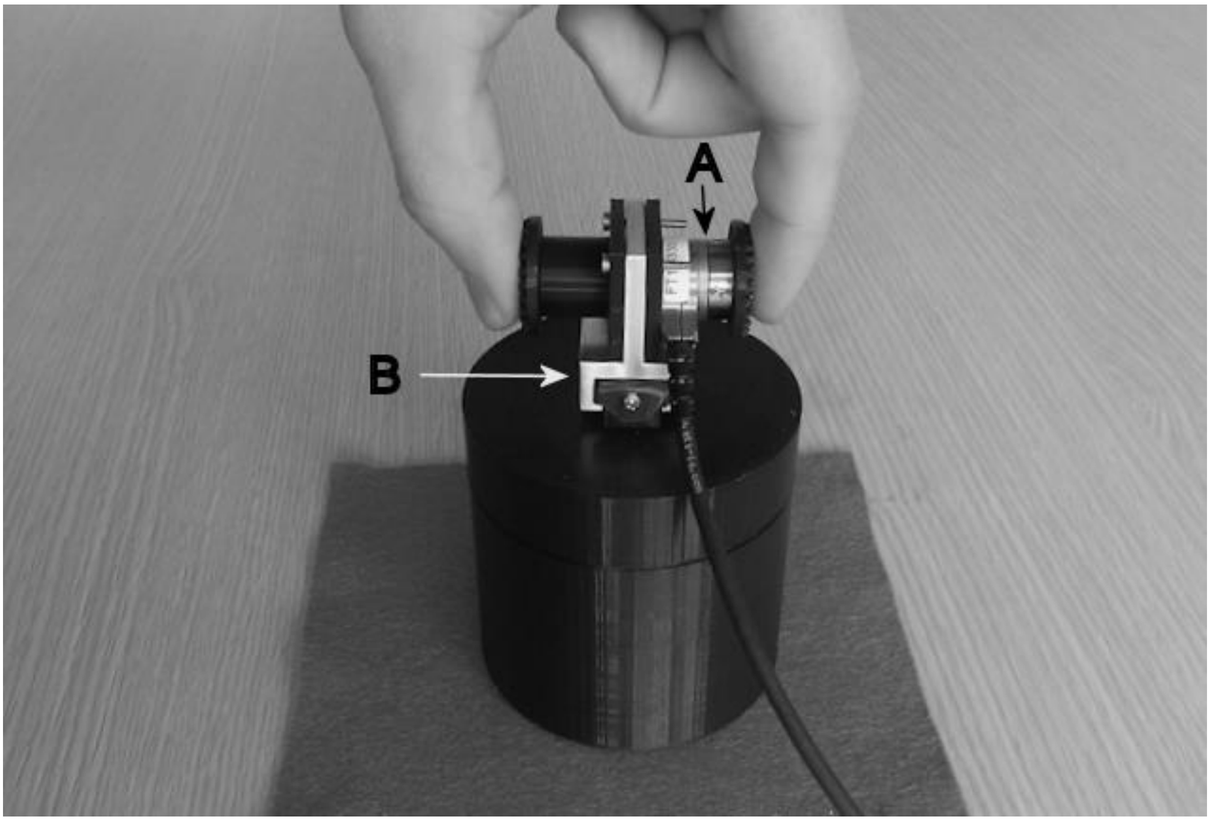
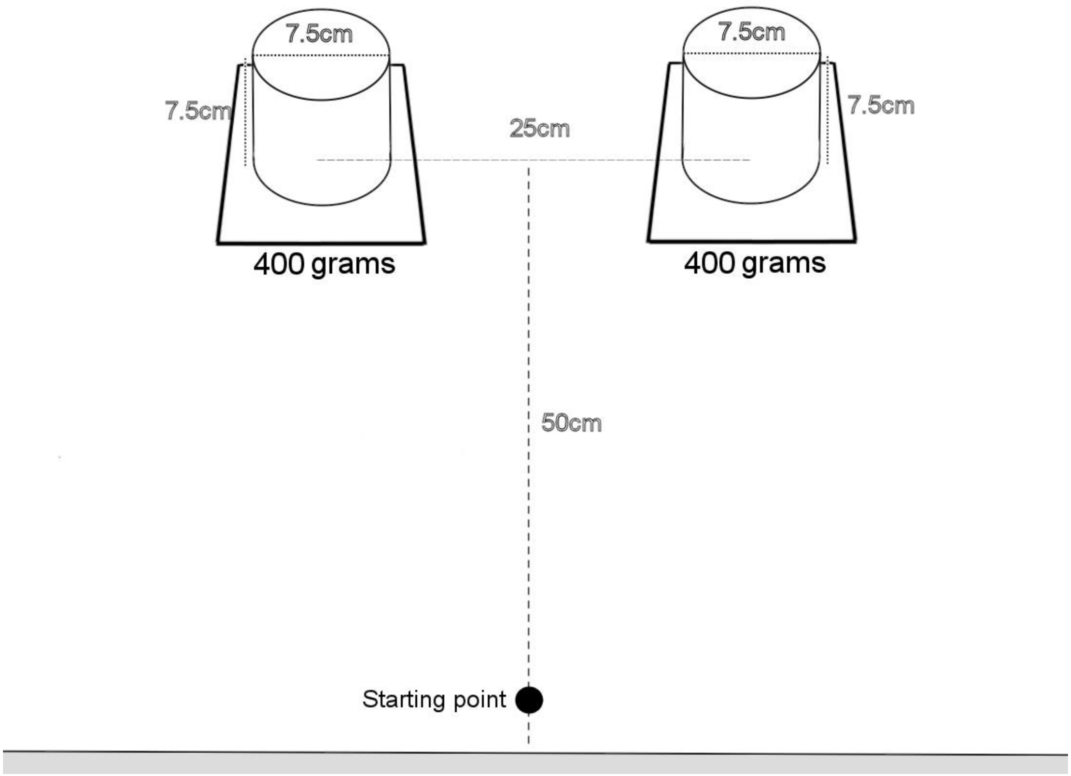
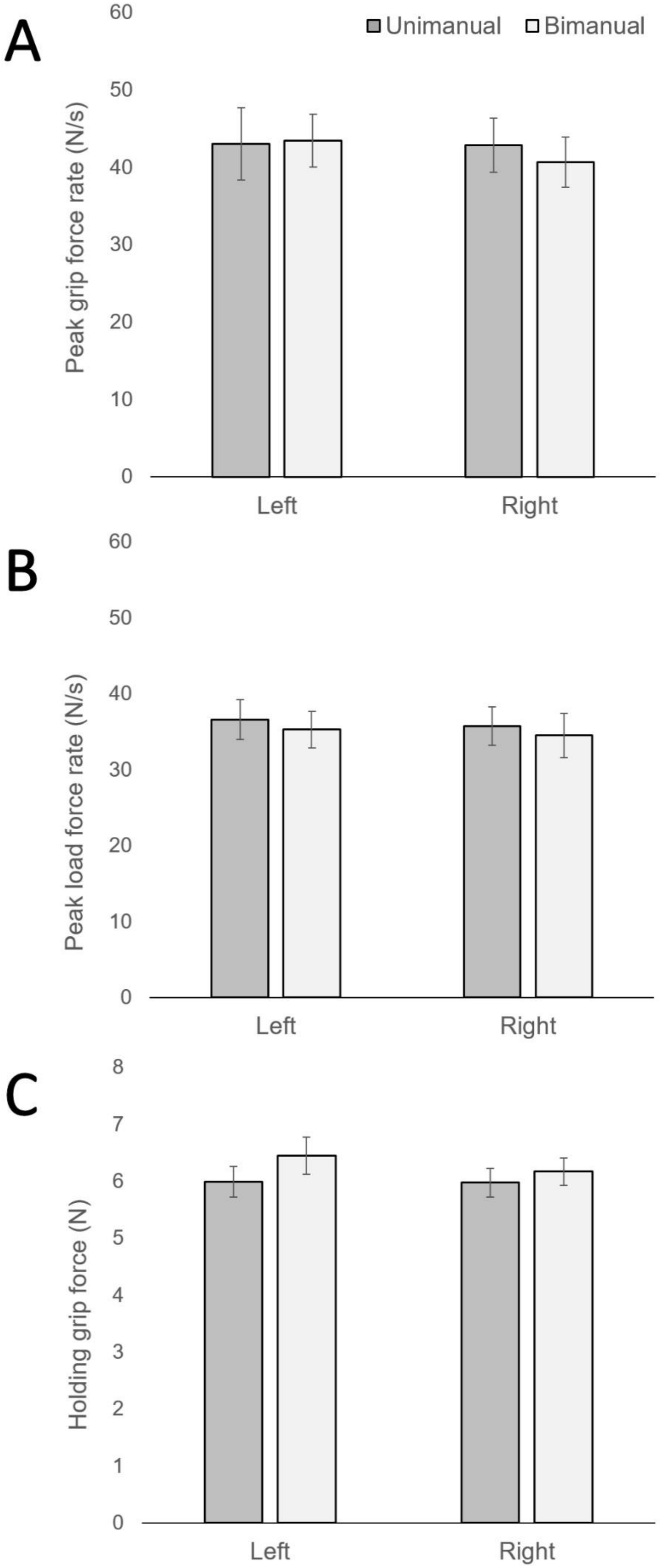
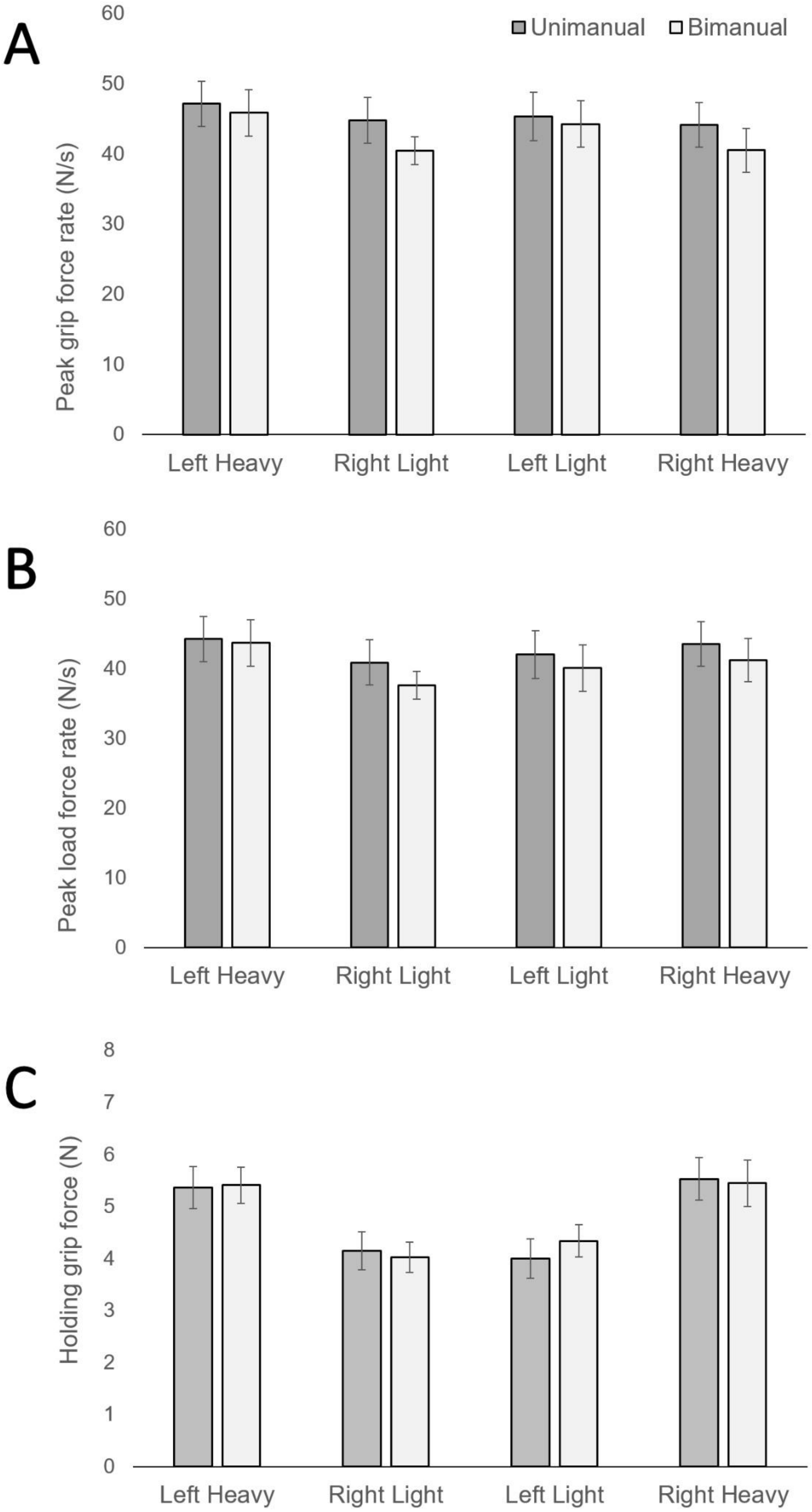
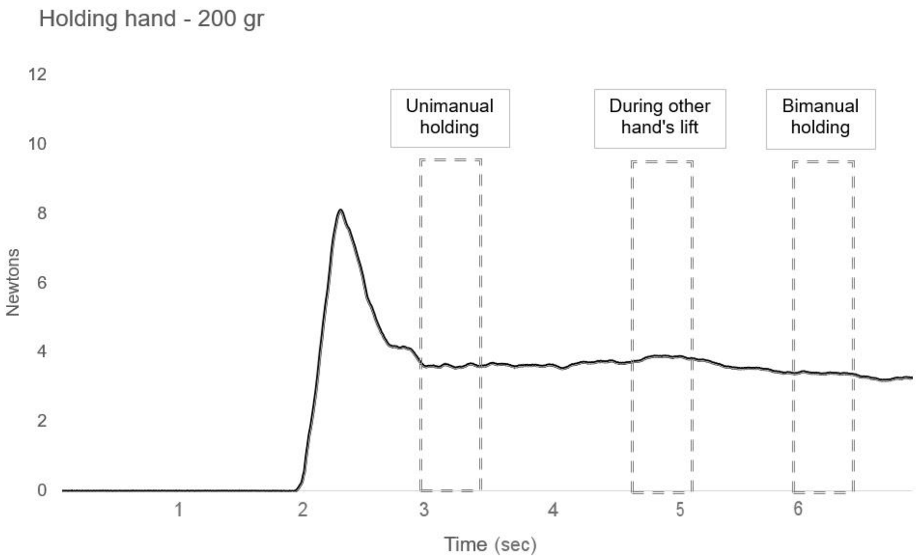
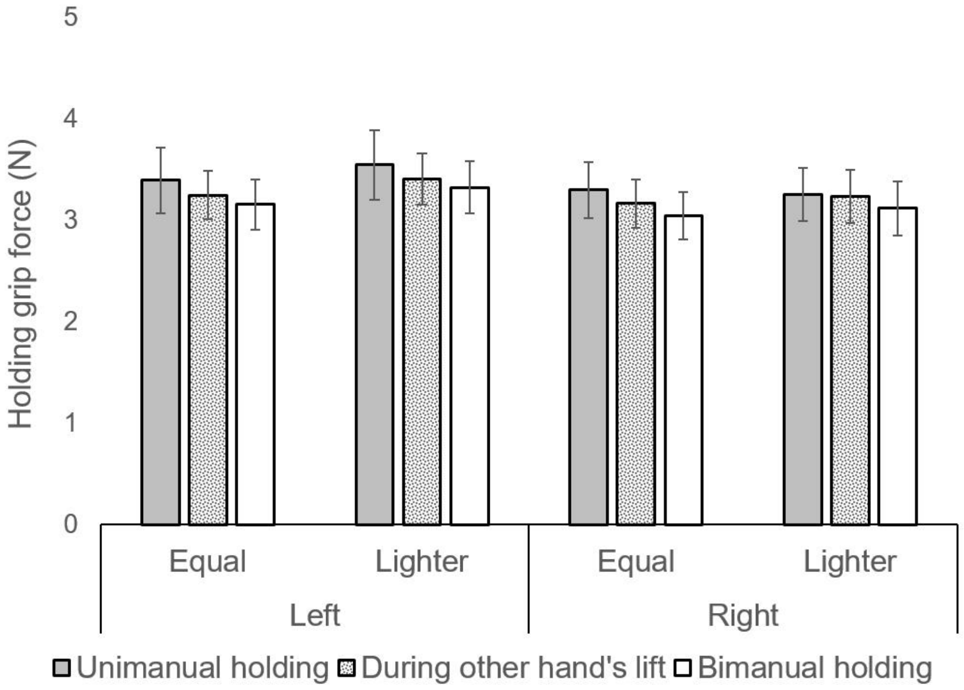

A
B

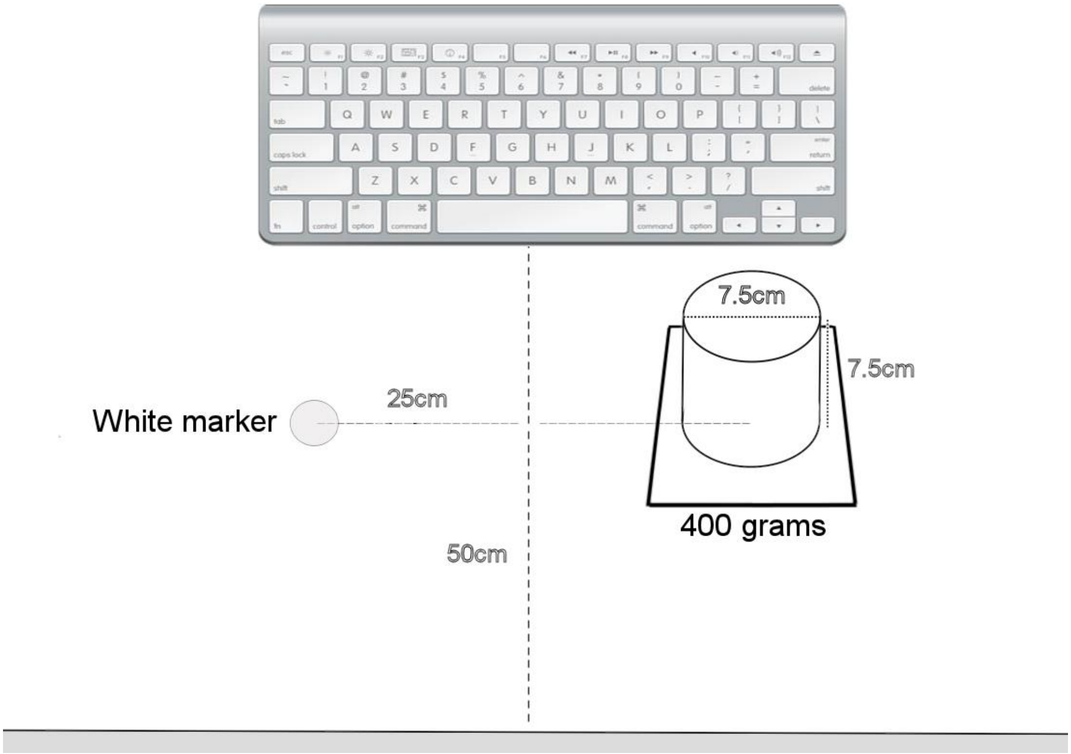

7.5cm
7.5cm
7.5cm
7.5cm
25cm
400 grams
400 grams
50cm
Starting point

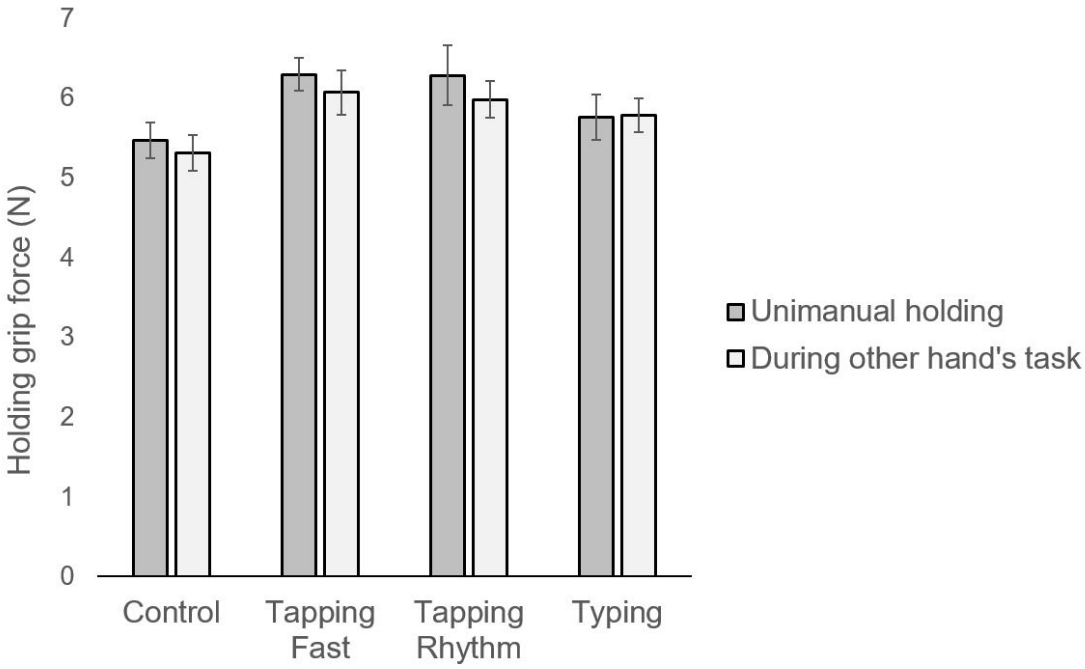

A
Unimanual
Bimanual
Peak grip force rate (N/s)
60
50
40
30
20
10
0
Left
Right
B
Peak load force rate (N/s)
60
50
40
30
20
10
0
Left
Right
C
Holding grip force (N)
8
7
6
5
4
3
2
1
0
Left
Right


A
Unimanual
Bimanual
Peak grip force rate (N/s)
60
50
40
30
20
10
0
Left Heavy
Right Light
Left Light
Right Heavy
B
Peak load force rate (N/s)
60
50
40
30
20
10
0
Left Heavy
Right Light
Left Light
Right Heavy
C
Holding grip force (N)
8
7
6
5
4
3
2
1
0
Left Heavy
Right Light
Left Light
Right Heavy


Holding hand - 200 gr
12
10
8
6
4
2
0
Newtons
Unimanual holding
During other hand's lift
Bimanual holding
1
2
3
4
5
6
Time (sec)


5
4
3
2
1
0
Holding grip force (N)
Equal
Lighter
Equal
Lighter
Left
Right
Unimanual holding
During other hand's lift
Bimanual holding


7.5cm
7.5cm
White marker
25cm
400 grams
50cm


Holding grip force (N)
0
1
2
3
4
5
6
7
Control
Tapping Fast
Tapping Rhythm
Typing
Unimanual holding
During other hand's task