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RESEARCH ARTICLE

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Grip forces when passing an object to a partner

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Abstract The goal of the present study was to investigate how grip forces are applied when transferring stable control of an object from one person to another. We asked how grip forces would be modified by the passer to (1) control for inertial forces as the object was transported toward the receiver and (2) control for the impending perturbation when the receiver made contact with the object. Twelve volunteers worked in pairs during this experiment. One partner, playing the role of passer, transported an object with embedded load cells forward or held the object at an interception location. The second partner, playing the role of receiver, waited at an interception location or reached toward the passed object. Kinematic results indicated that while passers performed a stereotypical movement, receivers were sensitive to the motion of the object as they reached to make contact. Grip force results indicated that passers' grip forces and grip/load force ratios were variable on a trial-to-trial basis, suggesting that a refined internal model of the passing task was not achieved within the timeframe of the experiment. Furthermore, a decoupling of the temporal and magnitude characteristics of the grip and inertial forces was noted in conditions where passers transported the object toward the receiver. During object transfer, it was noted that passers used visual feedback-based anticipatory control to precisely time initial grip force release, while somatosensory control was used by both the passer and receiver to precisely coordinate transfer rate.

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Introduction

Humans have remarkable skill for the performance of manipulative activities. With apparent ease, we manipulate countless objects with our hands, with the intent of using the objects as tools, repositioning the objects on a work surface, or gathering information about the objects through the sense of active touch. Beyond our ability to manipulate simple inanimate objects, we also have the capability to coordinate our actions with those of a partner to collaboratively manipulate objects. Consider, for example, a surgeon grasping a scalpel from an operating room nurse, or simply "passing the salt" to a dinner companion.

Past research using kinematic and grip force measures has provided us with a basic theoretical understanding of the underlying control processes used in the performance of simple manipulative activities and the use of sensory information for the regulation of reach to grasp and object positioning tasks (see MacKenzie and Iberall 1994; Wing, Haggard and Flannagan 1996 for reviews). However, the underlying control and sensory processes for activities where two separate effectors controlled by two separate persons are coordinated for task completion has only recently received attention (Schmidt et al 1990, 1998; Burstedt et al 1997; Churchill et al 1999; Simoneau et al 1999; Mottet et al 2001). Gaining a deeper understanding of this type of activity is important for several reasons. First, in practical terms, tasks where objects are transferred between people are common in our daily lives. Unfortunately, current theories of movement control deal mainly with activities, such as simple prehensile movements, where the individual components (such as sensory processors, effectors, and so on) reside within a single control system. Tasks such as passing prehension require the coordination of multiple, disconnected control systems. Thus, an important theoretical question regards how this coordination between disconnected neural controllers can occur such that these movements are made with such simplicity and elegance. A second important reason for studying tasks such as passing prehension relates to our understanding of the role of programming versus sensorimotor control of movements (Simoneau et al 1999). By using kinematic and grip force measures to study the temporal and spatial evolution of passing movements from the perspectives of both the passer and receiver, we can infer the roles of feedforward and feedback information in prehensile control using a complex functional activity. Finally, unlike simple prehensile movements which are completely predictable, passing prehension represents a semi-predictable task. Specifically, each partner may have a basic internal model regarding the evolution of the movement and may be able to use this model to predict the progression of the passing movement as a whole. However, there will necessarily be unpredictable aspects to the passing task given that control by one partner cannot be fully predicted by the other partner. Understanding how internal models are used/developed for semi-predictable tasks can be effectively investigated using a passing prehension task and will allow for the elaboration of this theoretical perspective.

Passing prehension tasks can be broken down into several underlying phases (MacKenzie and Iberall 1994; Cutkosky and Hyde 1993) with some overlap between the phases as the object is transferred between the two collaborators. First, the passer must present the object to the receiver. To accomplish this task, the passer can either transport the object toward the receiver, or simply hold the object while the receiver reaches to grasp it. Once the receiver has made initial contact with the object, load transfer can occur. To safely transfer the object, the passer must decrease grip force on the object while the receiver increases grip force. During this time, both partners must share the production of adequate grasp forces on the object to counteract gravitational and inertial load forces and thus prevent the object from slipping. Finally, when the receiver has produced sufficient grip forces on the object to maintain stable control, the passer can release his/her grasp.

As the passer transports the object toward the receiver, we must consider the grip forces that the passer produces to maintain a stable grasp. Flannagan and Wing (1993, 1997) studied movements of the arm with a grasped object in hand. They found that grip force was modulated in parallel with inertial load forces, with the grip force anticipating changes in the load force. Flannagan and Wing (1993, 1997) proposed that the central nervous system (CNS) has an internal model of the dynamics of the object and can predict the trajectory of the object. Thus, anticipatory control and a subtle interplay between feedforward and feedback mechanisms are used to maintain object stability during self-produced movements (Wolpert and Kawato 1998; Wolpert and Ghahramani 2000). However, when an object is transported with the goal of transferring it to another person, one must also consider the effects of object contact by the receiver. Receiver contact can be thought of as causing a mild collision with the passer/object. Turrell et al (1999) investigated anticipatory grip force control when subjects produced and received collisions from external objects. Their results indicated that when subjects had prior knowledge regarding the magnitude of the collision, they increased grip force in advance of the collision and scaled the increase to the anticipated perturbation forces. These authors concluded that subjects demonstrated knowledge of the dynamics of the collision and used this knowledge to update internal forward models in anticipation of the impending collision.

Extending these results to an object passing task, we investigated how the passer combined the effects of self-movement and the externally-produced collision to transport an object toward a receiver. As described by Flanagan and Wing (1993, 1997), grip force control on the object could be modified along with the inertial load forces exerted on the object due to its resultant acceleration. However, given the impending perturbation at object contact by the receiver, another possible anticipatory strategy for the passer would be to instead choose an initial grip force level sufficient to counteract both inertial and impact forces, and maintain that level throughout object transport (Turrell et al 1999). Thus, understanding the role of anticipatory control on the regulation of grip forces by the passer was a primary goal of the current study.

During object transfer, both the passer and receiver share responsibility and control of object stability. However, the ultimate goal of this shared responsibility is also different for each partner. Specifically, the passer's goal is to safely release the object, while the receiver's goal is to acquire the object into a stable grasp. Given these two separate but common goals, each subject must produce adequate, goal-specific grip forces on the object. We investigated how feedforward information and haptic feedback were used and coordinated by both the passer and receiver to apply task appropriate grasp forces during object transfer.

In a recent experiment, Burstedt et al (1997) demonstrated that feedforward anticipatory control was exhibited for object texture when two people cooperatively lifted an object with their right index fingers. For both cooperative and single-subject grasps, Burstedt et al (1997) found that the increase in grasping forces prior to object lift-off reflected digit-specific anticipatory mechanisms that predicted the final force requirement. Subjects also adapted the grip/load force ratios employed at each digit to the local frictional conditions such that adequate safety margins were maintained. Finally, slip-induced motor responses resulting in increased grip forces during the hold phase of the grasp movement appeared after a short latency ($\sim$70 ms), even when two subjects shared the task. Results from this study indicate the use of both anticipatory parameter control and somatosensory feedback control for the shared production of grasp forces during cooperative tasks. Furthermore, these results indicate that grasp stability can be mediated by neural controllers that are independent in terms of neural connections.

In the present study, we examined how the passer and receiver coordinated independent neural controllers to ensure timely and safe object transfer. We investigated how the task of object stability was shared by both partners as the object was transferred. Furthermore, we studied the temporal evolution of grip force release by the passer and grip force increase by the receiver.

Materials and methods

Participants

Twelve (six female, six male) healthy right-handed human volunteers, ranging in age from 18 years to 23 years, participated in this study. Subjects had normal or corrected-to-normal vision. Ethical approval from the Simon Fraser University Research Ethics Committee was obtained before testing began. Participants had no prior knowledge of the experiment and provided informed consent before beginning the study. Each subject participated in the experimental session for approximately one hour and was provided a small honorarium for participation.

General procedure

Two subjects of the same gender worked together as a collaborative pair, with one subject playing the role of passer, and the second subject playing the role of receiver. The task goal was to pass an object from passer to receiver within a designated interception zone (see Fig. 1a). Subjects sat opposite one another at a table with their right shoulders in line. Each subject either moved toward the interception zone or was stationary, for a total of four conditions (passer stationary, receiver stationary; passer stationary, receiver moving; passer moving, receiver stationary; passer moving, receiver moving). After each of the four conditions had been performed, with one subject playing the role of passer and the second subject playing the role of receiver, the subjects switched roles, and the four conditions were repeated. Ten trials were performed in a blocked order for each of the conditions for a total of eighty collaborative trials.

For the *moving passer* conditions, the passer began each trial holding the object a few centimeters above a start position located on the table. On the verbal "Go" signal, the passer transported the held object from the

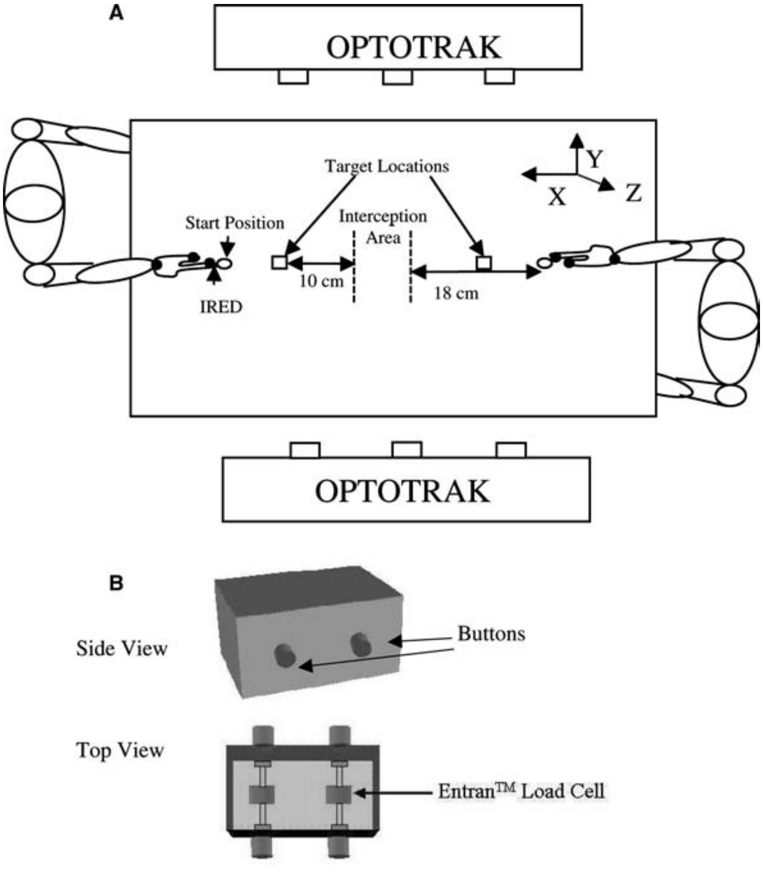


Fig. 1A–B **A** Layout of the experimental set-up. Movements by the passer and receiver were tracked by a two-camera OPTOTRAK motion analysis system. Passers either moved the object from the start position to the interception area or held the object in the interception area. Receivers either reached from the start position to the interception area or held their hand at the interception area to grasp the object. The transfer of the object was made in the interception area. **B** Schematic of object. Subjects grasped the buttons protruding from either side of the object with their index fingers and thumbs. Entran load cells were imbedded into the object and the buttons were screw-mounted onto the load cells to ensure that grasp forces were centered on the load cells start position toward the interception area, located midway between the passer and receiver. For the *stationary passer* conditions, the passer held the object over the interception zone, a few centimeters above the table, and waited for the receiver to make contact with the object.

For the *moving receiver* conditions, the receiver started with the index finger and thumb lightly pressed together over a start position located on the table. On the verbal "Go" signal, the receiver moved from the start position toward the interception zone, to make contact with the object. The receiver then grasped the object and moved it back over the target area. For the *stationary receiver* conditions, the receiver waited at the interception area with the grasping hand open, aperture slightly larger than the size of the object. Once the object was within the interception zone, the receiver closed the hand down on the object to grasp it and move it back over the target area.

Apparatus

A two-camera OPTOTRAK 3020 3-D motion analysis system (Northern Digital Inc., Waterloo, ON, Canada) monitored infrared emitting diodes (IRED) positioned on the index fingers, thumbs, and wrists of the passer and receiver as well as an IRED positioned on the top center of the object. Signals from the IREDs were sampled at 200 Hz and had an RMS accuracy of 0.1 mm.

For the conditions where the object was transported toward the interception zone by the passer, position data from the IRED located on the object was used to derive inertial load forces being applied as the object was transported by the passer. The weight of the object was known ($m = 90$ g) and the acceleration of the object could be computed from the OPTOTRAK data by differentiating the data twice. To assess the accuracy of the acceleration values obtained when the position data was double-differentiated, we placed an LED on a stationary object, collected a 1 s trial, filtered the data at 7 Hz and double-differentiated it. The resulting root mean square error had a value of 1.01 mm/s^2, which is negligible given that average resultant accelerations were in the range of 2,500 mm/s^2. Inertial load forces were calculated using the following equation:

$$F_{\text{inertial}} + {}_{\text{load}} = \sqrt{ma^2_{\text{sagittal}} + ma^2_{\text{horizontal}} + m(a_{\text{vertical}} + 9.81)^2}$$

For the conditions where the object was held stationary by the passer at the beginning of the trial, object motion-induced accelerations were negligible.

Grip force data were recorded using two load cells (model ELFM-T2, Entran Devices Inc.) imbedded 2.3 cm from each end of the black rectangular object (length = 8.4 cm; height = 5.5 cm; width = 3.3 cm). Each load cell had a range of ±25 N and a linearity of ±0.125 N. Four red cylindrical buttons (diameter = 1.4 cm) were screw-mounted on either side of each load cell, and served as the grasping surfaces (see Fig. 1b). Note that this constrained where the subjects were able to position their fingers to grasp the object. However, this constraint also ensured that grasp forces would be approximately centered over the load cell and that differences due to changes in torque could also be minimized. By ensuring that subjects always grasped the object in the same position, we assumed that the torque forces caused by grasping the object off-center would be the same for all trials. To assess the repeatability of the force measurements over the grasping surface, loads of between 150 g and 800 g were placed at the center of each button at distances of 0.35 cm from the center. Variations of the measurements from the center to the 0.35 cm distance were less than 5% for each of the applied loads. Thus all grip force results in the current paper must be interpreted with the limitation that they are accurate within ±5%.

The signals from the two load cells were amplified (model PS30A-1, Entran Devices Inc.) and transferred to a personal computer by means of a 12-bit analog-to-digital (A/D) converter (OPTOTRAK Data Acquisition Unit: ODAU). The sampling frequency for the grasp force measurements was 1,000 Hz. Subsequent to completion of the experiment, the collected data were transferred to a Sun workstation for analysis.

Data processing and analysis

Phase 1: object transport by passer/reach to grasp by receiver

This phase includes a description of the kinematic data for the passer and receiver and grasp force data for the passer as the object was transported from the start position toward the interception zone. The start of each partner's movement was determined from wrist velocity profiles as the first point when velocity increased above 5 mm/s, and continued to increase for more than 50 frames. The end of movement for each partner was determined as the time when the receiver made initial contact with the object. For each partner, the following kinematic-dependent measures were quantified: movement time, peak velocity, and percent time from peak velocity (time from peak velocity to end of movement, calculated as a percentage of total movement time).

To quantify the passer's grip force during object transport for the passer moving conditions and hold phase for the passer stationary conditions, the initial grip force (the force on the first frame of data collection) and the grip force at receiver contact were computed.

Phase 2: object transfer

This phase occurred when *both* the passer and receiver were in contact with the object. The start of this phase occurred when the receiver's hand first made contact with the object. Receiver contact was quantified by finding the peak rate of force increase and working backward in the trial to the first frame where grip force rate dropped below 0.08 N/s. The end of this phase occurred when the passer's hand released contact with the object. Passer release was defined as the first frame when the passer's grasp force reached the zero baseline value and continued at that value for a minimum of 50 frames.

The dependent measures used to quantify this phase of the passing movement were chosen to provide a description of the spatial and temporal coordination between passer and receiver during object transfer. The dependent measures were: transfer time, horizontal object displacement during transfer, vertical object displacement during transfer, peak rate of grasp force decrease by the passer (absolute value), peak rate of grasp force increase by the receiver, and time from object contact to peak grip force rate for each partner. Also, in order to evaluate the coordination of object transfer between the passer and receiver, we quantified the time difference between object contact by the receiver and the time at which the passer initially began decreasing grasp force on the object. The time at which the passer began decreasing grasp force was determined by locating the peak rate of force decrease by the passer and working backward in the trial to the first valley in the grip force rate profile (see Fig. 2).

Statistical analyses

For the dependent measures quantifying object transport by the passer, separate two-receiver movement (receiver stationary, receiver moving) repeated measures analyses of variance (ANOVA) were computed. Similarly, for the dependent measures quantifying reach to grasp by the receiver, separate two-passer movement (passer stationary, passer moving) repeated measures ANOVA were computed. Finally, for the dependent measures quantifying transfer of the object between partners, separate two-receiver movement (receiver stationary, receiver moving) × two-passer movement (passer stationary, passer moving) repeated measures ANOVA were performed. Because of the exploratory nature of this work, an a priori alpha level of $P < 0.05$ was set to determine significance for all statistical tests. Tukey's honestly significant difference (HSD) test was performed post hoc on all significant effects.

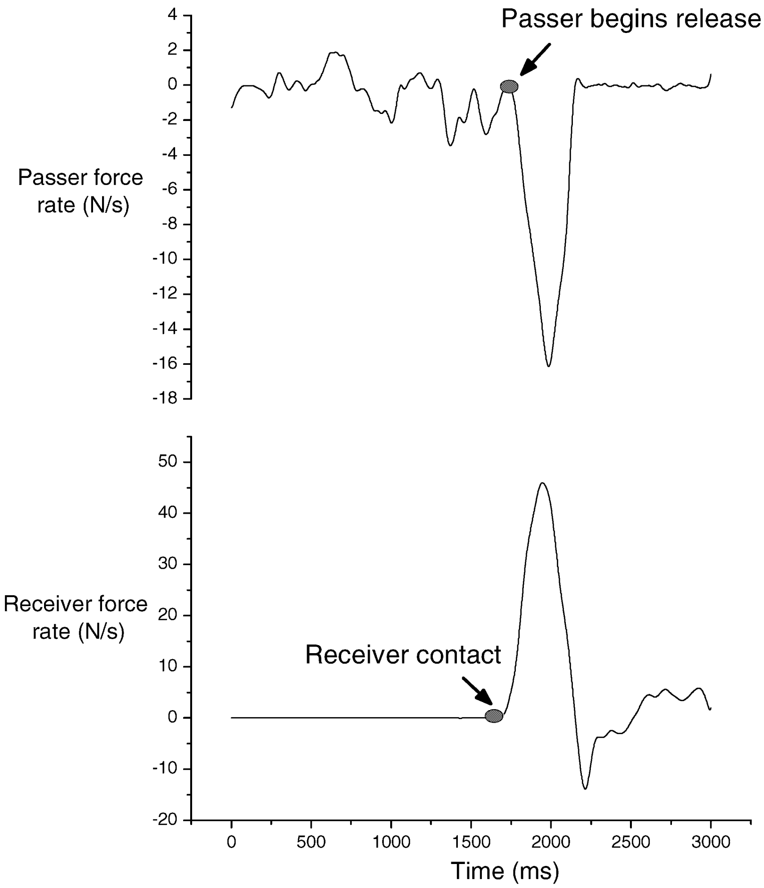


Fig. 2 Grip force rate decrease for the passer and increase for the receiver, showing how receiver contact and passer decrease were quantified. Receiver contact was quantified by finding the peak rate of force increase and working backward in the trial to the first frame where grip force rate dropped below 0.08 N/s. The time at which the passer began decreasing grasp force was determined by locating the peak rate of force decrease by the passer and working backward in the trial to the first valley in the grip force rate profile

Results

Phase 1: object transport by passer/reach to grasp by receiver

Statistical analyses revealed that, regardless of whether the receiver moved toward the interception zone or simply waited at the interception zone, the passers' movement time ($F_{(1,11)} = 0.05$, $P = 0.82$), peak velocity ($F_{(1,11)} = 0.19$, $P = 0.67$) and percent time from peak velocity ($F_{(1,11)} = 0.34$, $P = 0.58$) to transport the object from the start position to the interception zone were similar. For both conditions, the passer's average movement time was 1,169 ± 28 ms, average peak velocity was 496 ± 16 mm/s, and average percent time from peak velocity was 57.6 ± 0.9%. In contrast, main effects were found for the receiver's movement time ($F_{(1,11)} = 7.4$, $P = 0.02$) and peak velocity ($F_{(1,11)} = 10.12$, $P = 0.008$). Movement time was longer and peak velocity was lower when receivers reached for an object held by a moving passer (MT = 1,025 ± 46 ms; PV = 650 ± 33 mm/s) than when they reached for an object held by a stationary passer (MT = 909 ± 50 ms; PV = 698 ± 30 mm/s). There were no significant effects for the receiver's percent time from peak velocity ($F_{(1,11)} = 0.45$, $P = 0.52$; average = 51 ± 2%).

Figure 3 illustrates grip forces profiles for all trials performed in each of the four conditions (ten trials per condition) for two subject pairs. Note the high variability in initial grip forces for both passers in each of the four conditions. The average standard deviation for initial grip force was 1.3 N within condition and was similar for each of the conditions (range 1.0–1.5 N). Furthermore, initial grip forces did not appear to become more consistent as the trials progressed within a condition.

Despite the high variability of initial grip forces within conditions, grip forces by the passer were similar across conditions. We computed the passer's initial grip force and grip force at receiver contact. The main effects of passer movement ($F_{(1,11)} = 3.9$, $P = 0.08$), receiver movement ($F_{(1,11)} = 0.08$, $P = 0.78$) and the interaction between passer and receiver movement ($F_{(1,11)} = 2.9$, $P = 0.12$) failed to reach significance for the passer's average initial grip force. Regardless of whether they moved the object toward the interception zone, or held it stationary, or whether the receiver reached to grasp the object or remained stationary at the interception zone, the passers' mean initial grip force was 6.9 ± 0.9 N. Furthermore, the main effects for passer movement ($F_{(1,11)} = 0.56$, $P = 0.48$), receiver movement ($F_{(1,11)} = 0.24$, $P = 0.64$) and interaction between passer and receiver movement ($F_{(1,11)} = 1.5$, $P = 0.25$) for the passers' grip force at object contact by the receiver failed to reach significance. The passers' average grip force at receiver contact was 6.0 ± 0.6 N. Thus, passers used a similar grip force across conditions when transporting or holding the object before receiver contact. It is interesting to note from these average grip forces that the trend was for passers to decrease grip force slightly during the time between the initiation of the trial and receiver contact and then decrease grip force sharply following receiver contact (see Fig. 4 for examples). Specifically, for the majority of trials (90%) the change in grip force from the beginning of the trial to receiver contact was less than 1.5 N/s. For the remaining 10% of the trials, the change in grip force was larger than 1.5 N/s. Although the 10% of trials during which large grip force decreases occurred could indicate the use of different transport and release strategies, the small percentage of trials make this hypothesis difficult to test with the current results.

Figure 4 further illustrates the passers' grasp forces as they transported the object from the start position to the interception zone or held the object at the interception zone for the receiver. In Fig. 4, resultant object position, grip force, inertial + load force and force ratio are presented for the passer and receiver for all conditions. Consistent with the results presented in Fig. 3, the grip force used by the passer to hold the object at the interception zone was variable within condition, such that passers chose different grip forces and grip force ratios to maintain a stable grasp on the object before receiver contact on a trial-to-trial basis. Furthermore, as seen in the grip force and force ratio profiles in Fig. 4, passers did not alter the grip/load force ratio prior to receiver contact, regardless of whether they began the trial with an elevated grip force or not. Thus, although contact by the receiver can be thought of as a producing a mild collision or impact with the passer/object, in the stationary passer conditions, impending impact by the receiver did not cause the passer to increase grip force on the object.

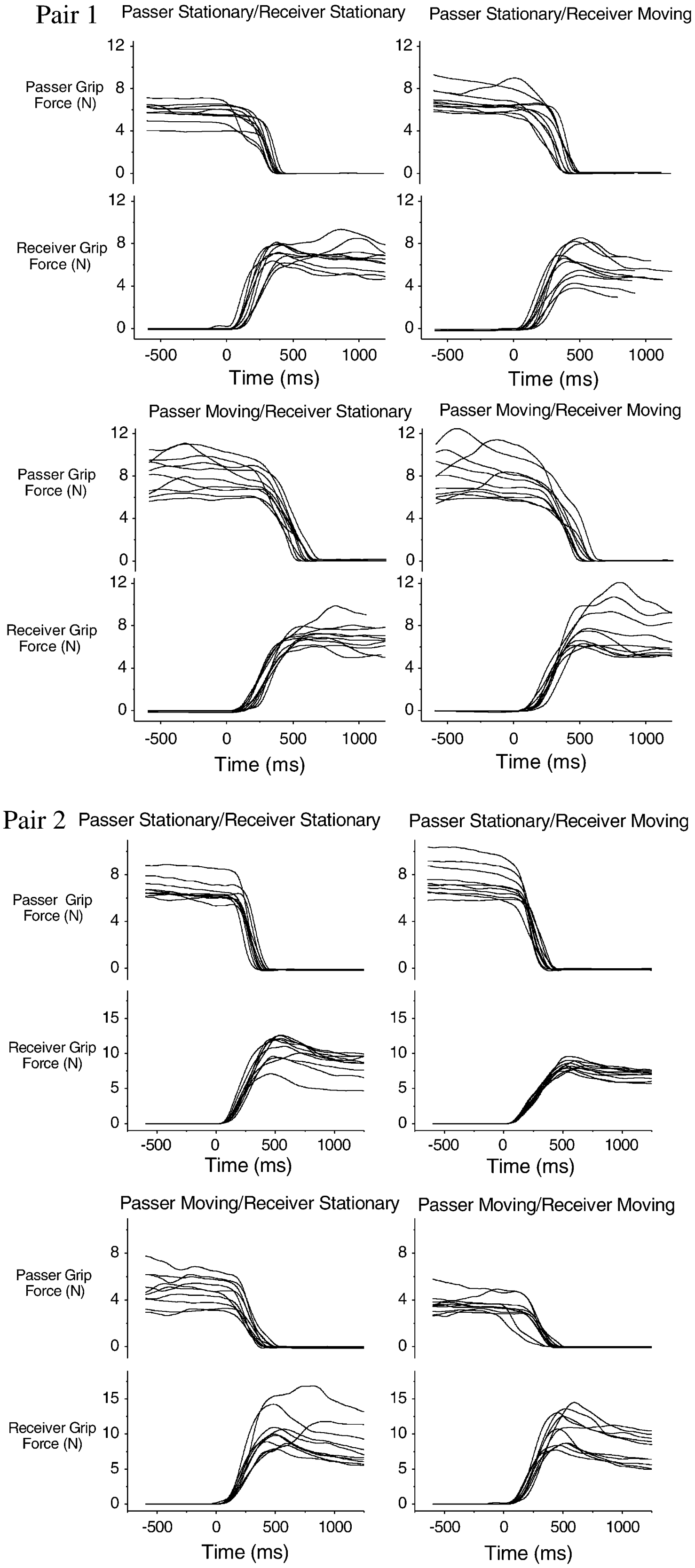
Finally, as seen in Fig. 4, for the majority of moving passer trials, grip force profiles and force ratios were not modified along with changes in inertial load. In fact, grip forces and force ratios remained fairly stable from the moment the passer began to move toward the interception zone until the moment where the receiver made contact with the object.

Phase 2: object transfer

Results of the two (passer movement) × two (receiver movement) ANOVA for transfer time indicated that the length of time required to transfer control of the object from the passer to the receiver was approximately 500 ms, and was not affected by either the movement of the passer ($F_{(1,11)} = 0.11$, $P = 0.75$) or the receiver ($F_{(1,11)} = 0.83$, $P = 0.38$). Furthermore, the interaction between passer and receiver movement failed to reach significance for transfer time ($F_{(1,11)} = 0.47$, $P = 0.51$).

Despite similar transfer times for all conditions, the horizontal and vertical displacement of the object during transfer varied as a function of condition. There was a main effect of passer movement on horizontal displace-

Fig. 3 Representative grip force profiles for two subject pairs in each of the four conditions. All passing trials (10) in each condition have been plotted. For ease of comparison, all profiles have been aligned such that object contact by the receiver occurs at time = 0 ms. Note the high variability in initial grip force for both passers in each of the four conditions. Also note that the passer's grip force achieves the baseline 0 N value at approximately 500 ms after contact by the receiver in each of the four conditions, signaling complete transfer of the object from passer to receiver



ment of the object during transfer ($F_{(1,11)} = 34.2$, $P < 0.001$), however, an interaction between passer and receiver movement was also found ($F_{(1,11)} = 25.2$, $P < 0.001$). Figure 5a illustrates this interaction. Post hoc analysis revealed that all means were significantly different. However, horizontal displacement of the object during transfer was greater for a stationary passer when the receiver moved toward the interception zone, than when the receiver was stationary. In contrast, displacement was greater for a moving passer when the receiver waited stationary than when the receiver moved toward the interception zone.

There were main effects of both passer ($F_{(1,11)} = 68.2$, $P < 0.001$) and receiver ($F_{(1,11)} = 7.3$, $P < 0.021$) movement on vertical displacement of the object during transfer; however, a significant interaction between receiver movement and passer movement ($F_{(1,11)} = 6.2$, $P < 0.03$) indicated that vertical displacement of the object was greater for a stationary passer when the receiver was moving, while displacement was similar for a moving passer regardless of whether the receiver was stationary or moving (see Fig. 5b).

For absolute peak grip force rate, results of the two (role: passer, receiver) × two (passer movement) × two (receiver movement) ANOVA revealed a role main effect ($F_{(1,11)} = 6.9$, $P = 0.02$). The peak rate of grasp force increase by the receiver was significantly greater than the peak rate of force decrease by the passer (receiver: 45.9 N/s; passer: 32.6 N/s). Role also interacted with passer movement ($F_{(1,11)} = 7.1$, $P = 0.02$). Post hoc analysis indicated that peak force rates for the passer and receiver were similar when the passer was stationary; however, when the passer moved, the receiver's peak force rate was significantly higher that the passer's peak force rate (see Fig. 6). Despite the effects of role and partner movement on peak grip force rate, time to peak grip force rate was unaffected by either manipulation. Both partners achieved peak grip force rate 275 ± 9 ms after object contact by the receiver.

Finally, we were interested in evaluating the temporal coordination between object contact by the receiver and grasp force release by the passer. We quantified how soon the passer began releasing grasp forces on the object before/after object contact by the receiver. On average we found that the passer began releasing grasp forces 19.8 ± 9 ms after the receiver made contact. Although there was not a main effect for passer movement ($F_{(1,11)} = 0.45$, $P = 0.5$), a main effect was found for receiver movement ($F_{(1,11)} = 35.05$, $P < 0.001$). Results indicated that, when the receiver was stationary, the passer began releasing grasp forces 36 ± 9 ms after receiver contact; however, when the receiver was moving, the passer began releasing grasp forces approximately 3 ± 10 ms after the receiver made contact with the object. The interaction between passer and receiver movement failed to reach significance ($F_{(1,11)} = 0.54$, $P = 0.48$). Plots of the relative timing of contact by the passer and release by the receiver in the four movement conditions are shown in Fig. 7.

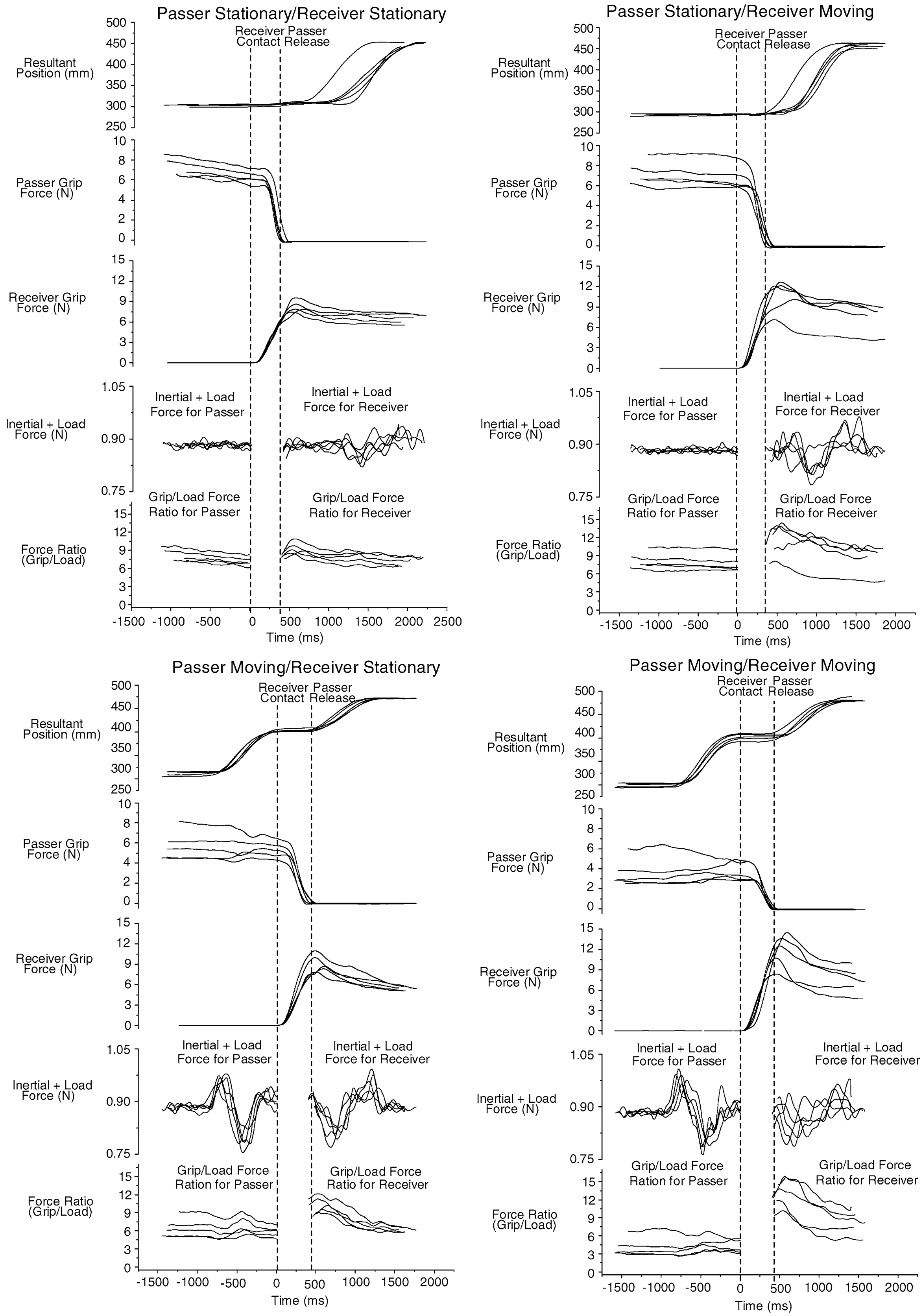
▶

Fig. 4 Force profiles produced by the passer and receiver for all conditions. The data have been aligned at receiver contact, which is represented as time = 0 ms on each graph. In each panel, resultant position, passer grip force, receiver grip force, inertial + load forces and grip/load force ratio have been plotted. The *horizontal dashed lines* represent receiver contact (*left line*) and passer release (*right line*). As expected, when the passer held the object stationary in the interception zone, the resultant position did not change, and thus inertial/load forces remained stable on the object. Consistent with the profiles shown in Fig. 3, initial grip forces on the object were variable within conditions, which resulted in variable, but constant grip/load force ratios. Of interest is that passers did not appear to modify their grip forces or force ratios in anticipation of receiver contact in the passer stationary conditions, regardless of the magnitude of grip force production prior to receiver contact. For the moving passer conditions, inertial/load forces increased as the object was first accelerated toward the interception zone and then decreased as the interception zone was approached. Of interest is that the grip force profiles were not modified along with changes in inertial load. Note that there are no values for inertial + load forces as well as grip force ratios during object transfer. Because object acceleration was used to calculate load force, it is impossible to determine the load experienced separately by the passer and receiver during this time

To further illustrate the relationship between receiver contact and passer release, the distribution of release times by the passer with respect to object contact by the receiver is presented in Fig. 8 for the four conditions. It is worth noting that, for conditions where the receiver was stationary, the most common release times for the passer were between 60 ms and 120 ms after receiver contact (passer stationary–receiver stationary) and greater than 120 ms after receiver contact (passer moving–receiver stationary). In contrast, when the receiver moved, the passer most commonly released the object 0–60 ms before receiver contact (passer stationary–receiver moving) or 0–60 ms after receiver contact (passer moving–receiver moving).

Discussion

In the current experiment, we investigated the movements made by passers and receivers to transfer stable control of an object from one person to another. We were specifically interested in examining the grip forces produced by the passer as the object was transported and transferred to a partner. We studied how grip forces were modified by the passer to (1) control for the inertial forces as the object was transported toward the receiver and (2) control for the impending perturbation when the receiver made contact with the object. We investigated how the coupling between grip and inertial load forces was modulated by the passer during transport of the object toward the interception zone. We also investigated the use of anticipatory and sensorimotor mechanisms for stable transfer of the object between partners. The question of interest is: how are the two separate neural controllers coordinated to ensure timely and successful transfer during a passing prehension task?


Passer Stationary/Receiver Stationary
Passer Stationary/Receiver Moving
Passer Moving/Receiver Stationary
Passer Moving/Receiver Moving
Receiver Contact
Passer Release
Resultant Position (mm)
Passer Grip Force (N)
Receiver Grip Force (N)
Inertial + Load Force (N)
Force Ratio (Grip/Load)
Inertial + Load Force for Passer
Inertial + Load Force for Receiver
Grip/Load Force Ratio for Passer
Grip/Load Force Ratio for Receiver
Grip/Load Force Ration for Passer
250
300
350
400
450
500
0
2
4
6
8
10
3
9
12
15
0.75
0.90
1.05
-1500
-1000
-500
1000
1500
2000
2500
Time (ms)

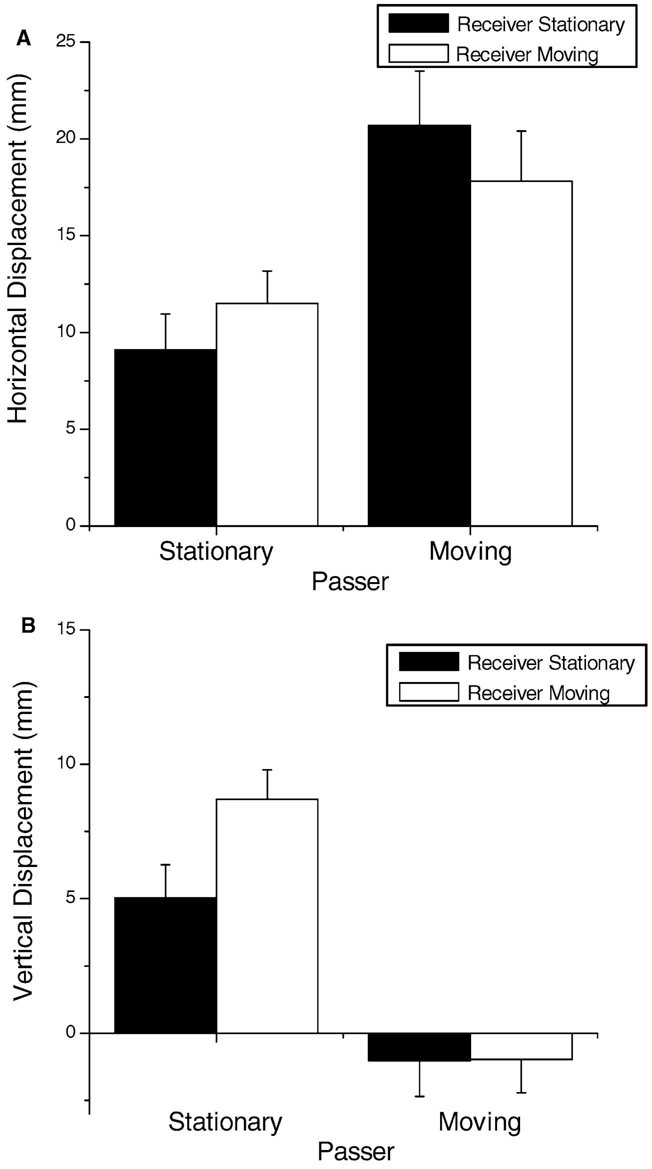


Fig. 5A–B Interaction between passer movement and receiver movement for **A** horizontal displacement of the object during transfer and **B** vertical displacement of the object during transfer. Horizontal displacement of the object was greater for a moving passer than for a stationary passer. Furthermore, the significant interaction indicated that displacement was greatest for a stationary passer when the receiver was moving and for a moving passer when the receiver was stationary. In contrast, vertical displacement of the object during transfer was greatest for a stationary passer. Furthermore, vertical displacement was greater for a stationary passer when the receiver moved; however, when the passer moved, vertical displacement was similar regardless of receiver movement

Phase 1: object transport by passer/reach to grasp by receiver

At the kinematic level, the passer's movements to transport the object toward the interception zone were unaffected by the movement of the receiver. Regardless of whether the receiver waited at the interception zone to grasp the object or moved toward the interception zone, the passer's movement time, velocity, and deceleration time did not differ significantly. These results are not surprising given that the passer was transporting the same object over the same distance in both the stationary and moving receiver conditions and was in control of the initial portion of the transfer task.

In contrast, the kinematic profiles for the receiver differed depending on whether they grasped the object from a stationary or moving passer. The receivers' movement times and peak velocities differed even though the targets to be grasped were always contacted within the target zone, and thus the distance traveled in approaching the target was always the same. These results indicate a task dependency in choosing an appropriate kinematic strategy for reaching to grasp the target (Marteniuk et al 1987). Our results show that receivers were sensitive to the motion of the target when it was passed by a partner, and that a conservative grasp strategy (in terms of longer movement time and lower peak velocity) was employed when receivers grasped objects that were transported by their partner in comparison to when the objects were held stationary.

The longer movement times and lower peak velocities found when the target was held by a moving passer also provide further evidence that subjects are sensitive to the motion of the target when grasping an approaching object (Carnahan and McFadyen 1996; Mason and Carnahan 1999). Mason and Carnahan (1999) showed that when targets were moving at a constant but slow velocity, subjects generated peak transport velocities that were even slower than when the target was stationary. Our results extend this to conditions where the target is held by another person and thus moves at a slow, but unpredictable velocity. These results provide evidence that subjects are sensitive to a target's motion and use characteristics such as target velocity when generating interception movements (Bootsma and Peper 1992; Carnahan and McFadyen 1996).

At the grasp force level, the passer chose an average grip force of approximately 6.9 N regardless of whether the object was held stationary at the interception zone, or was moved toward a moving or stationary passer. This lack of differences in both kinematic- and grasp force-dependent variables would seem to indicate that the passer, who was in complete control of the early phases of object transfer, was performing the same stereotypical movement for all trials. However, as shown in Figs. 3 and 4, variability in the initial grip forces and grip force ratios used by the passer were substantial across trials in each of the four conditions.

When subjects first experienced the passing task, they did not have any knowledge of the properties of the object to be passed, the various passing conditions, or how their partner would move to receive the object. Some knowledge of these task-related environmental properties is necessary for the generation and use of internal models (Imamizu et al 1995). Thus, it is unlikely that passers began the task with an accurate internal

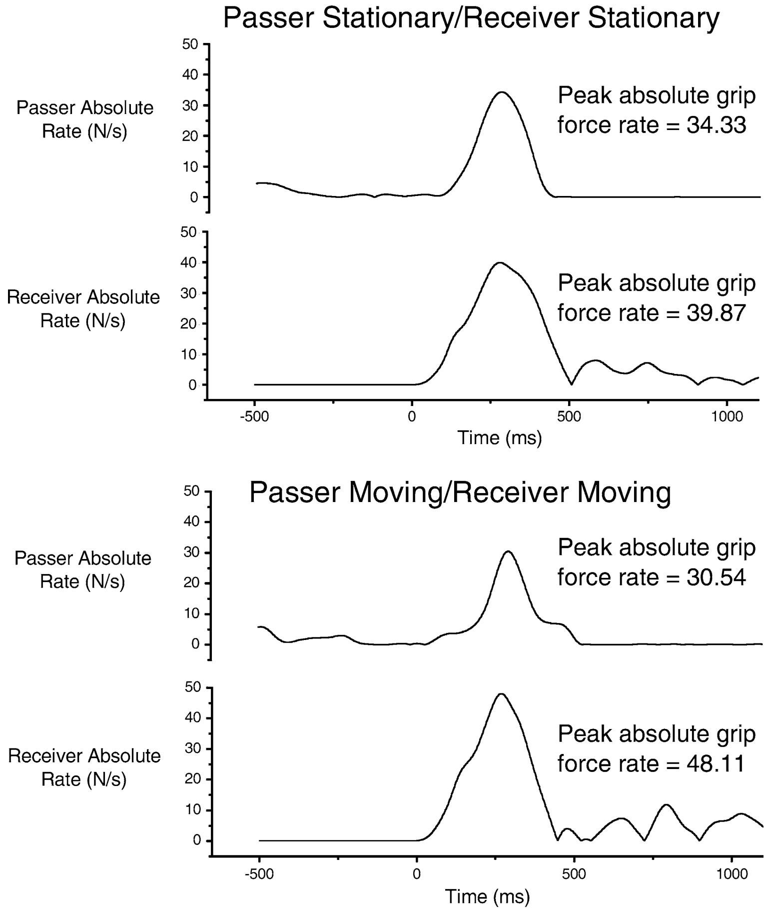


Fig. 6 Interaction between role (passer or receiver) and passer movement (stationary or moving) for absolute grip force rate. When the passer was stationary, absolute grip force rates were similar for the passer and receiver. However, when the passer was moving, the receiver's peak force rate was significantly higher than the passer's

model of the passing activity as a whole. However, we wondered whether this model would develop within the timeframe of the experiment, such that passers would produce consistent grip and load force patterns appropriate for the various passing conditions. The substantial variability in the starting grip forces, grip force ratios, and the decoupling of the grip and load forces for the passer throughout the current experiment give some indication that passers continuously experimented with and refined their motor plans for the passing task. Furthermore, the continued variability throughout the experiment could indicate that, within the timeframe of the current study, subjects did not achieve a refined internal model to accurately describe the interactions present within the passing activity. This is interesting given that, for many other tasks such as point-to-point arm movements (Flanagan and Wing 1993) and collisions with a predictable external object, subjects can develop accurate internal models within 15–20 trials. Perhaps, given the unpredictability of the receiver's movements, it would be impossible for the passer to generate an adequate model of the current task. On the other hand, perhaps given a greater number of trials, the most appropriate initial grip force, force ratio and release strategy would emerge as the result of a refined internal model. Specifically, an adequate model may only emerge with a highly practiced transfer task. The potential emergence of an internal model within an object passing task is an interesting notion that should be investigated further using a greater number of trials.

We were also interested in further considering conditions where the object was transported toward the interception zone by the passer to discover how inertial and impact forces would affect the passers' grip force. In recent years, studies have been conducted to investigate how grip and load force are coupled/decoupled when movements of hand-held loads are executed in healthy subjects as well as in patients (Flanagan and Wing 1993, 1997; Kinoshita et al 1996; Nowak et al 2003; Nowak 2004; Nowak and Hermsdorfer 2004). Results have indicated that during voluntary arm movements grip force is precisely modulated in parallel with fluctuations in the movement-induced inertial load (Nowak 2004). Flanagan and Wing (1993) also noted that in horizontal movements of objects, grip forces started to increase at the onset of movement and remained elevated until movement ceased. These authors concluded that changes in grip force anticipated fluctuations in the inertial force, suggesting that modulations in grip force are tightly coupled with inertial forces, and are planned in anticipation of the consequences of our own actions.

In the current experiment, we found neither temporal coupling (parallel fluctuations of grip force in anticipation or response to fluctuations in inertial force) nor

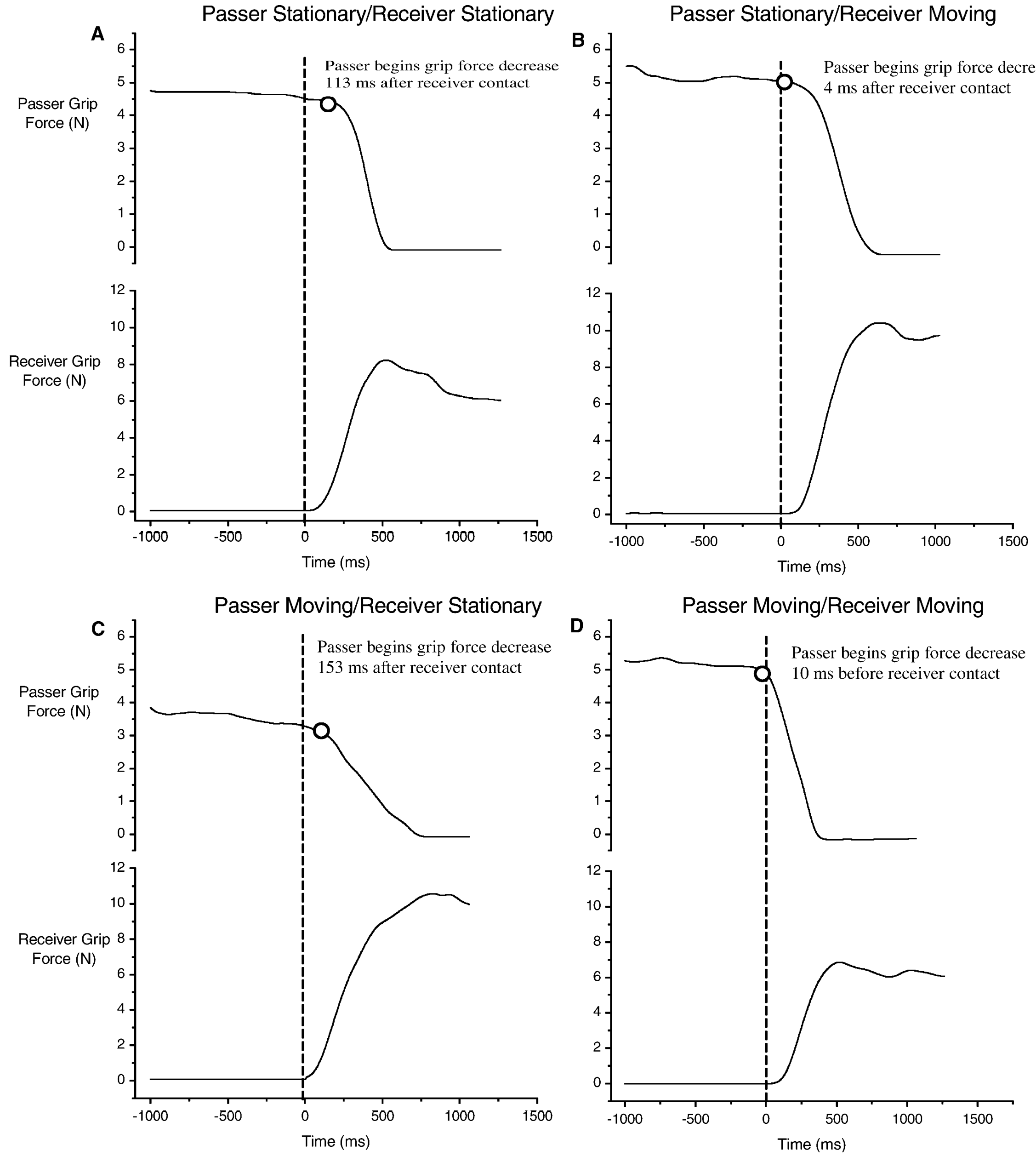


Fig. 7A–D Single grip force profiles for one subject pair (passer and receiver) in each of the four conditions. All trials have been aligned to receiver contact, which is represented as time = 0 ms on the graph. For ease of comparison, a *dashed line* has been drawn through the 0 ms mark. Note that when the object was grasped by a stationary receiver (panels **A** and **C**), the passer began releasing grip force several ms after receiver contact. However, when the receiver moved from the start position toward the interception zone, the passer began decreasing grip force at approximately the same time as the receiver made contact with the object (panels **B** and **D**)

coupling of the magnitudes of grip and inertial force as the passer transported the object toward the interception zone. Instead, for the majority of trials, passers started the trial with an elevated grip force and maintained or slightly decreased that force as they transported the object toward the receiver. This constant grip force was maintained although the inertial forces being applied to the object increased as the object was accelerated toward the interception zone and decreased as the interception zone was approached.

A flexible and task-dependent decoupling of the grip/load force relationship has recently been reported (Serrien and Wiesendanger 2001; Nowak and Hermsdorfer 2004). Serrien and Wiesendanger (2001) found elevated grip forces that did not coincide with increased load forces when subjects held an object during a bimanual grasp task. Serrien and Wiesendanger (2001) argued that the coordinative constraint between the magnitude of grip and load force is not fixed, but flexible in a task-dependent manner. Nowak and Hermsdorfer (2004)

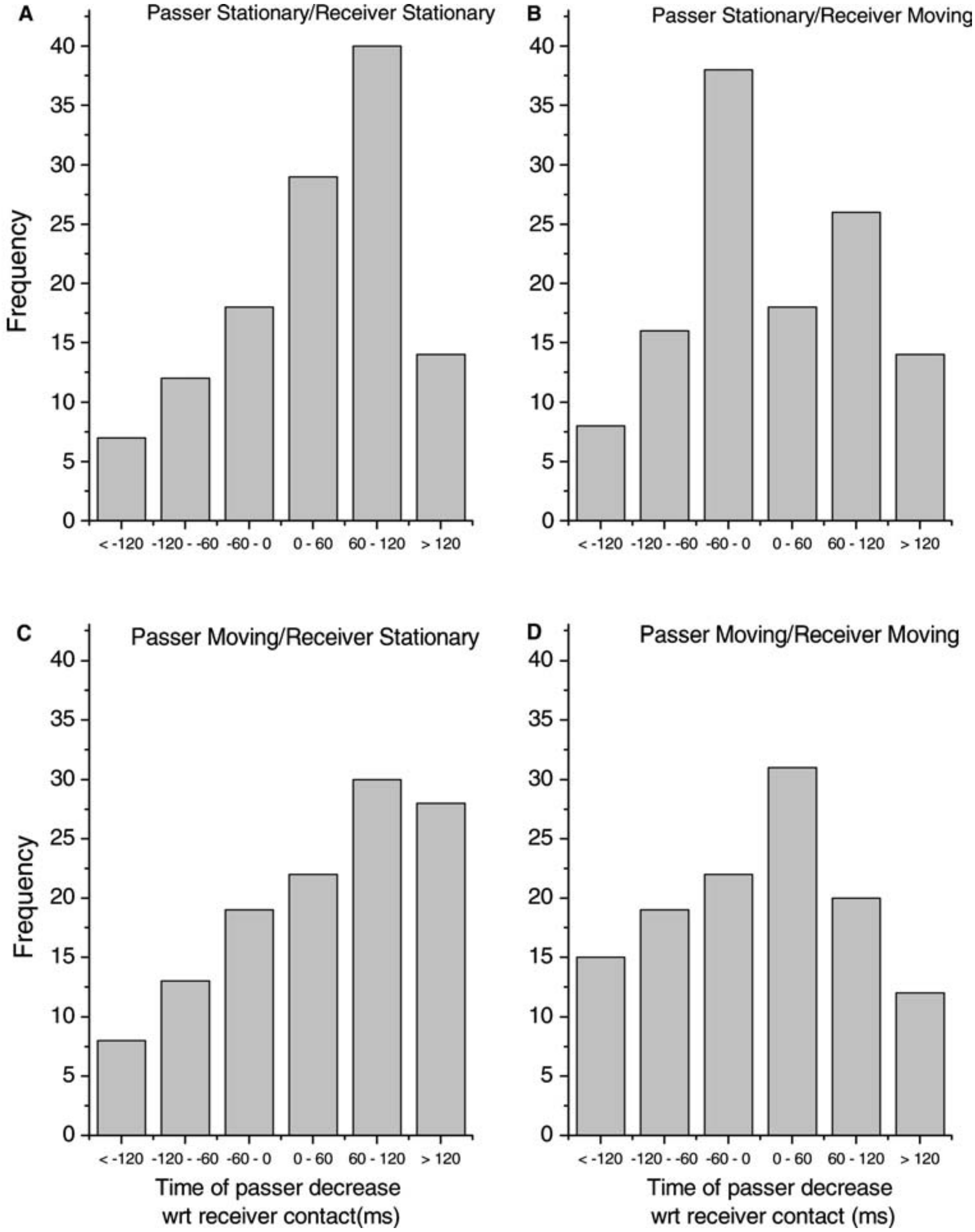


Fig. 8A–D Frequency distribution of times to the beginning of grip force release by the passer with respect to object contact by the receiver for each of the four conditions. Time categories are < -120 ms, -120 to -60 ms, -60 to 0 ms, 0 to 60 ms, 60 to 120 ms, and > 120 ms between object contact by the receiver and the beginning of grip force release by the passer. Note that when the receiver was stationary (panels **A** and **C**), the greatest distribution of grip force decrease times occurred in the time ranges greater than 60 ms; however, when the receiver was moving (panels **B** and **D**), the most common times were between -60 and 60 ms

reached a similar conclusion regarding the temporal coupling of grip and load force for results of a study in which an object was dropped from either a subject's other hand or the experimenter's hand. These authors found that when the object was dropped from the experimenter's hand, prediction of load force was less precise and resulted in more pronounced grip forces and grip force rates. These authors concluded that their observations indicated less precise temporal coupling between grip and load force profiles in the experimenter-release condition.

In the current experiment, it is possible that passers felt the greatest threat to object stability was object contact by the receiver. Given this potential threat, it appears that they chose to employ conservative initial grip forces which were sufficient to compensate for both movement-based inertial loads and impact force at receiver contact. Thus, grip and load force were decoupled as they transported the object toward the receiver. However, it is also possible that, given sufficient practice with the task and the emergence of a task-specific internal model, these initial grip forces would be reduced to load-appropriate levels, and coupling of the grip and load forces would be seen as passers transported the object toward the receiver. This notion should be further investigated to determine whether the elevated grip forces seen in the current experiment are the result of an intentional strategy, or the result of inexperience with the task.

Phase 2: object transfer

At the highest temporal level, the transfer of the object between partners seemed independent of the movement of either passer or receiver (the time required to transfer the object between partners remained consistent at 500 ms regardless of condition). Despite the similarity in transfer time between conditions, the actual movements being performed during object transfer were quite different. When the passer moved toward the interception zone, horizontal displacement was greater. In contrast, when the passer was stationary, vertical displacement was greater. It also appeared that the greatest displacement of the object in either the vertical or horizontal directions was achieved when one of the partners was moving while the other partner was stationary. Thus, although the temporal components of object transfer were consistent between conditions, spatial characteristics differed systematically with task. These differences in movement characteristics during object transfer provide evidence for a combined task-appropriate strategy shared between passer and receiver in dealing with the inertial forces present in the hand and object as the interception zone was approached. In particular, when the passer moved the object toward a stationary receiver, the task-appropriate strategy was to take advantage of the inertial forces being applied to the object by the passer, such that during transfer the object would continue to be moved in the direction of the receiver's final target location. In contrast, when a moving receiver reached to acquire the object from a stationary passer, the appropriate strategy was to slow the forward movement of the receiver at object contact. This was necessary because the receiver would ultimately have to change directions to transport the object back toward the target location. Slowing the receiver's forward motion was best achieved with both subjects moving the object in a vertical direction.

In the current experiment, we were also interested in considering how feedforward and feedback information sources were used to ensure stable and timely transfer of the object. We investigated how the rate of grip force decrease by the passer and the grip force increase by the receiver was coordinated as the object was transferred between partners. Results indicated a tight synchronization between the rates of change of grip force production on the object by both partners. Although the passer had a lower grip force rate than the receiver during object transfer, the time at which peak grip force rate occurred in all conditions, for both the passer and receiver, was the same. These results provide preliminary evidence for separate but coordinated feedback-based timing mechanisms, responsible for the temporal coordination of object transfer. Specifically, we have preliminary evidence that, within a few hundred milliseconds, each partner was able to use haptic feedback about their partner's force rates to control and modify their own grip force rates, such that the combined result ensured a synchronized and coordinated transfer.

The relationship between object contact by the receiver and grip force decrease by the passer also appeared to be synchronized for many trials. This tight temporal synchronization between object contact by the receiver and grip force decrease by the passer indicates that an anticipatory feedforward mechanism, using online visual information to predict receiver contact, was exploited by the passer to ensure timely object transfer (Lacquaniti 1996). We also found that in conditions where the receiver was moving, on average the passer began releasing grip force on the object synchronously with receiver contact. In contrast, when the passer was stationary, grasp force decrease occurred several milliseconds after receiver contact. These results indicate that the feedforward mechanism used by the passer was more accurate when the receiver reached to intercept the object. Specifically, when the receiver moved toward the interception zone, visual information included not only hand movement to close down on the object, but also limb movement toward the interception zone. This provided the passer with a richer source of visual feedback than in conditions where the receiver's limb was stationary at the interception zone and the hand simply closed down on the object. Thus, the ability to predict receiver contact earlier and more accurately was facilitated when the receiver moved to intercept the object. This conclusion is further supported by the distribution plots shown in Fig. 8.

Past work has shown that anticipatory changes in grip force are sensitive to the environmental demands of the task. Johansson and Westling (1988) observed that anticipatory increases in grip force on the cup occurred when subjects dropped a ball held in one hand into a cup being held by the other hand. These changes in grip force anticipated the increase in load force that resulted from contact between ball and cup. In Johansson and Westling's (1988) experiment, the anticipatory grip adjustments were task-dependent in that the prudent modulatory change was to increase grip force to guard against object slippage. In the current experiment, the opposite anticipatory modulation occurred. In fact, passers decreased grip force in anticipation of object contact by the receiver instead of increasing grip force to guard against dropping the object. How could the passers be certain that contact by the receiver would not cause the object to fall? In anticipation of both inertial and impact forces, passers chose an initial grip force that was higher than the minimum needed to safely hold the object.[1] This resulted in a moderate safety margin, allowing grip force to be decreased slightly without fear of dropping the object. Thus, we have evidence that the anticipatory mechanism here is sensitive to the environmental demands of the task. In this case, task com-

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[1] Note: slip forces were quantified post hoc on two subjects (including the primary author). We quantified slip force by having subjects hold the object such that it could be maintained parallel to the table surface for two seconds and then slowly release the object until it began to rotate. Results indicated that hold forces were consistent with data presented in the current experiment (4–7 N range) and slip forces varied between 2.8 N and 4.5 N. Thus, on average, the safety margin utilized by subjects in the current experiment was between 2 N and 4 N

pletion demands that the passer release the object in a timely fashion. By using a task-specific grip force and timing the start of grip force decrease to coincide with object contact by the receiver, the passer optimized the temporal components of object exchange.

In conclusion, our results indicate that at the level of grip force production on an object to be transferred, passers compensated for the novelty of the task and object by changing grip force application on a trial-by-trial basis. Thus, a refined and consistent internal model of the passing task was not achieved within the experimental timeframe. These force profiles also included a decoupling of the grip and inertial load forces by the passer. We propose that this decoupling may have occurred in the interest of ensuring stability as the receiver made contact with the object (particularly in the moving passer conditions) as well as providing for a timely release of the object. However, further experimentation is necessary to determine whether increased practice with the task would cause the emergence of an internal model resulting in less variable movements by the passer. Finally, during object transfer, we found that the passer used anticipatory control to time initial grip force release while somatosensory control was used by both partners to coordinate transfer rate.

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