Experimental Brain Research (2019) 237:2585–2594
https://doi.org/10.1007/s00221-019-05606-y

RESEARCH ARTICLE

# Grip force preparation for collisions

Irene A. Kuling[1,2] · Florian Salmen[1,2] · Philippe Lefèvre[1,2]

Received: 18 February 2019 / Accepted: 16 July 2019 / Published online: 1 August 2019


## Abstract

Grip force has been studied widely in a variety of interaction and movement tasks, however, not much is known about the timing of the grip force control in preparation for interaction with objects. For example, it is unknown whether and how the temporal preparation for a collision is related to (the prediction of) the impact load. To study this question, we examined the anticipative timing of the grip force in preparation for impact loads. We designed a collision task with different types of load forces in a controlled virtual environment. Participants interacted with a robotic device (KINARM, BKIN Technologies, Kingston) whose handles were equipped with force sensors which the participants held in precision grip. Representations of the hand and objects were visually projected on a virtual reality display and forces were applied onto the participant's hand to simulate a collision with the virtual objects. The collisions were alternating between the two hands to allow transfer and learning between the hands. The results show that there is immediate transfer of object information between the two hands, since the grip force levels are (almost) fully adjusted after one collision with the opposite hand. The results also show that the grip force levels are nicely adjusted based on the mass and stiffness of the object. Surprisingly, the temporal onset of the grip force build up did not depend on the impact load, so that participants avoid slippage by adjusting the other grip force characteristics (e.g., grip force level and rate of change), therefore considering these self-imposed timing constraints. With the use of catch trials, for which no impact occurred, we further analyzed the temporal profile of the grip force. The catch trial data showed that the timing of the grip force peak is also independent of the impact load and its timing, which suggests a time-locked planning of the complete grip force profile.

**Keywords** Grip force · Timing · Motor planning · Anticipation · Collision

## Introduction

Interaction with moving objects while holding another object is something we do very regularly in our daily life, e.g., when playing tennis or holding a tray while someone (un)loads it. One of the challenges in these types of tasks is to apply a sufficient grip force on the hand-held object to counteract tangential load forces due to the collision.

When manipulating an object in precision grip, the changes in load force can be predicted by the neural system because of the efference copy of the arm motor command, and be compensated by anticipatory grip force adjustments to stabilize the object. Hereby, the force level of the grip and the load are coupled with no time delay (Flanagan and Wing 1993; Flanagan and Tresilian 1994), including changes of the load force due to position, velocity and acceleration (Flanagan and Wing 1997; Nowak et al. 2004).

When hand-held objects are perturbed from an external source, it becomes more difficult to predict changes of the load force, especially when the load force change is fast and the available time for sensory feedback is short, like in the case of a collision. Several studies have addressed the control of grip force in collision tasks (e.g., Johansson and Westling 1988; Serrien et al. 1999; Nowak and Hermsdörfer 2006). When the impact load was predictable, participants were able to adjust their grip force to the impact time and intensity during passive collisions (Johansson and Westling 1988) as well as during active collisions (Turrell et al. 1999). During passive collisions, when the task was to

Irene A. Kuling and Florian Salmen contributed equally to this work.

✉ Philippe Lefèvre
philippe.lefevre@uclouvain.be

1 Institute of Neuroscience (IoNS), Université catholique de Louvain, Brussels, Belgium

2 ICTEAM, Université catholique de Louvain, Louvain-la-Neuve, Belgium

receive and withstand an impact, the timing of the grip force peak regarding the load force peak was delayed (Serrien et al. 1999; Turrell et al. 1999; Delevoye-Turrell et al. 2003). An earlier study from Johansson and Westling (1988) attributed this delay of the grip force peak to a reactive response, whereas a more recent study from Bleyenheuft et al. (2009) suggested that the predictive nature of grip force during rapid load force changes was causing the delays. Bleyenheuft et al. introduced catch trials in their protocol, in which an expected collision did not happen, and no load force was applied on the hand-held object. During these catch trials, the delayed grip force peak was still present, revealing its predictive nature. White et al. (2011) expanded on that study using catch trials in active collisions in a virtual environment and demonstrated that the timing of the grip force peak delay is pre-programmed and does not adapt to different load forces.

The research studying grip force in collision-like loads has focused often on the grip force response at or after the impact but rarely on the grip force preparation in anticipation of the collision. Johansson and Westling (1988) reported an anticipatory rise in grip force around 150 ms prior to the impact, but it is unknown whether and how the temporal preparation for a collision is related to the prediction of the impact.

In the present study, we examined the anticipative timing of the grip force in preparation for the impact load. To do this, we designed a collision task with different types of load forces in a controlled virtual environment. The results reveal that the temporal onset of the grip force build up does not depend on the impact load, so that participants avoid slippage by adjusting the other grip force characteristics (e.g., grip force level and rate of change), therefore considering these self-imposed timing constraints. Also, the timing of the grip force peak is independent of the impact load, which suggests a time-locked planning of the grip force profile.

## Methods

### Participants

Nineteen healthy participants (eight men, two left-handed, average age $31.7 \pm 13.5$ years) participated in the experiment after they provided informed consent (including one of the authors, FS). They all had normal or corrected-to-normal vision and did not have any known oculomotor deficiencies or motor disabilities. Except for the author, the participants were naïve as to the purpose of the experiment and debriefed after the experimental session. The data of the author were not different from the data of the others and the outcomes of the statistical tests were not affected with or without the data of the author. The experimental procedures were approved by the local ethics committee at the Université catholique de Louvain.

### Behavioral task

We studied grip force anticipation and grip force adaptation to different load forces in a passive collision task alternating between the two hands. Participants were asked to hold two manipulandum handles (one for each hand), attached to a robotic arm, between thumb and index finger in a precision grip. This enabled the participants to interact bimanually in a 2D plane with virtual objects displayed on a virtual reality display (KINARM, BKIN Technologies, Kingston) (Fig. 1b). Two force sensors on each manipulandum recorded the grip and load force of the index finger and thumb of each hand (Fig. 1a). Direct vision of the limbs and robotic arms was blocked. The participants were instructed to keep each hand in a visually indicated start position and await and absorb the collision(s). The target moved towards their hand and then collided with a virtual bar attached to their hand. The visual virtual bar was presented orthogonal to the movement of the ball (Fig. 1d), and did not rotate along with possible handle rotations. We instructed the participants to hold the rotation of the handle in such a way that the ball would collide orthogonal to the line between their thumb and index finger, and we instructed them not to lose the grip of the manipulandum during the collision and not to push against the incoming object. The movement of the handle in the direction of the approaching ball before the collision was typically less than 3 mm. Due to the impact of the collision, the hand typically moved back less than 5 mm.

### Task protocol

In the experiment, we wanted to investigate how the anticipatory grip force timing interacts with grip force adaptation to different load forces in a collision task. A second aim was to investigate transfer and learning of this grip force anticipation between the two hands. To elicit various load force profiles, we presented virtual objects to the participants of two different object stiffnesses ($k1 = 1000$ N/m, $k2 = 6000$ N/m) and three different masses ($m1 = 2$ kg, $m2 = 4$ kg, $m3 = 8$ kg) resulting in six distinct objects (Fig. 1c). The object collisions were presented in blocks. One block consisted of six trials with the same object characteristics and all objects moved at the same constant velocity when approaching the hand. The six consecutive trials allowed us to study the evolution of the responses within each block. Thirty blocks of six trials were performed for each of the six objects resulting in $30 \times 6 = 180$ blocks ($180 \times 6$ collision $= 1080$ collisions in total). Half of the blocks started with a collision to the left and the other half with a collision to the right. All

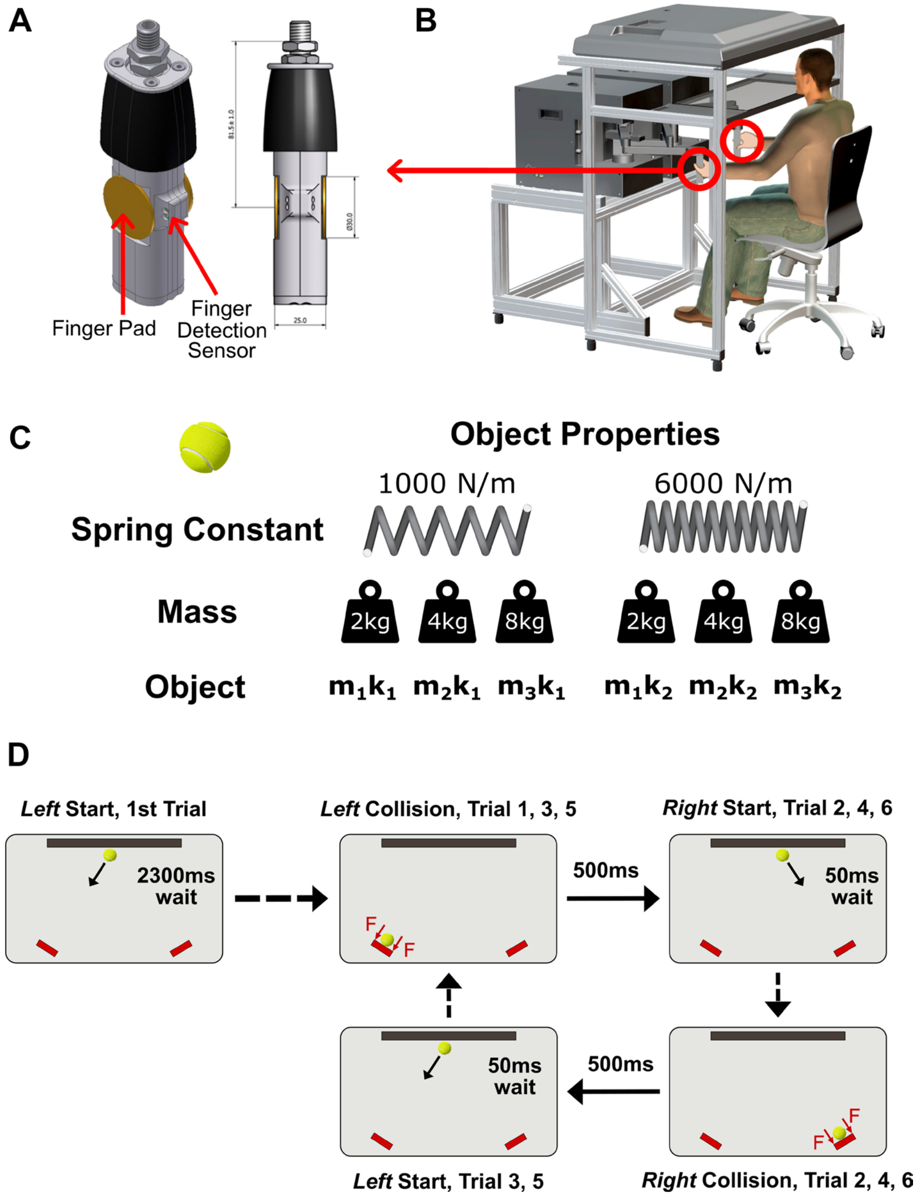


**Fig. 1** **a** Handle with manipulandum and force sensors. Two different viewing angles. **b** KINARM setup, handles held in precision grip. **c** Properties of virtual objects used during experiment. Two stiffnesses ($k1=1000$ N/m, $k2=6000$ N/m) and three different masses ($m1=2$ kg, $m2=4$ kg, $m3=8$ kg) constitute six different objects represented by a tennis ball image (3 cm diameter). **d** Time course of a block. One block consisted of a sequence of six trials. The participant's hands, represented by the red oblique bars are put into the indicated position. In the first trial, after 2 s of fixation and a gap period (object blanked for 300 ms), the object started moving towards the first hand (here: left hand) at a constant velocity (60 cm/s). After ≈ 380 ms, the object collided with the red oblique bar, triggering a force impulse onto the participants hand depending on mass and spring constant of the object. After the collision, the object bounced back in the direction where it came from for another 500 ms. Then the second trial started and after another 500 ms, the object was shown for 50 ms until it started moving towards the other hand (here: right hand), collided with it and bounced back for 500 ms. Then the third trial started and after another 500 ms, the object is shown again. Each block contained one randomly chosen catch trial (note that the first trial is never a catch trial) in which no force was applied

blocks of one starting direction were bundled so that participants did a series of 90 blocks in one starting direction and then 90 blocks in the other starting direction. The starting direction was counterbalanced across participants. The distribution of objects was randomized, so that the participant did not know what object and intensity of the impact to expect in the first trial of each block. In addition, each block contained one catch trial in which no force was applied to measure the mechanically unperturbed grip force. The catch trial was chosen randomly for each block and could replace normal trials 2–6 of a block (the first trial of block was never a catch trial).

During the entire experiment, a horizontal bar (30 × 2 cm) was shown on the top of the screen as reference for the starting position of the moving objects that collided with the participant's hand. At the beginning of the first trial of each block, the participants were asked to move both handles, represented by two oblique rectangular bars (1.5 × 5 cm, rotated (anti-)clockwise by 32.66° from the horizontal axis), into their indicated positions which were 30 cm apart from each other. Five hundred milliseconds after that, the virtual object (image of a tennis ball, 3 cm diameter) was displayed around 25 cm away from the hands, just below the horizontal reference bar (Fig. 1d).

In the first trial of a block the object was displayed for 2000 ms until it was turned off once for 300 ms to indicate the start of the object movement. For the subsequent trials 2–6, the object was only displayed for 50 ms before it started moving. The object moved orthogonally towards the oblique rectangular bar (object velocity 60 cm/s) and collided with it. At contact, the object bounced back and was shown for another 500 ms. According to the virtual object mass and stiffness, different impact forces were applied by the robot to the hand approximating real-world collision dynamics modeled after Hooke's law. The force at a certain moment in time $F_t$ was determined by the stiffness $k$ of the object and the penetration length of the object into the handle at the same moment in time $x_t$:

$$F_t = k \times x_t.$$

The applied force $F_t$ determined the updated velocity $V_{t+1}$ and position $X_{t+1}$ of the virtual object:

$$V_{t+1} = V_t - \frac{F_t}{m} \times \Delta t,$$

$$X_{t+1} = X_t + V_{t+1} \times \Delta t,$$

where $\Delta t$ is the time step between state $t$ and $t + 1$ and $m$ is the virtual object mass.

## Experimental setup

For this experiment, we used a KINARM robot (BKIN Technologies, Kingston; acquisition rate 1000 Hz) whose handles were equipped with a KINGRIP manipulandum (Arsalis, Belgium; acquisition rate 1000 Hz). Each KINGRIP manipulandum was held in a precision grip between the thumb and index finger while manipulating the robot arms. Each KINGRIP finger contact surface (brass) was equipped with a bi-directional force sensor recording the normal force (range = 100 N, non-linearity < 0.3%) and the horizontal tangential force (range = ± 50 N, non-linearity < 0.3%) applied by each finger on the KINGRIP manipulandum. The analog KINGRIP force signals were filtered with a Bessel 8-pole low pass filter with a cutoff frequency of 500 Hz.

## Data analysis

Throughout the whole experiment, the grip and load force at both handles were measured (typical profile see Fig. 2). Also, the position of the hands, the timing of collisions and the collision forces were measured. Data were analyzed offline using MATLAB and repeated measures ANOVA conducted with SPSS. Graphs were created with MATLAB and Inkscape was used to edit them and create illustrations.

For each trial, we calculated several metrics on grip force level and grip force timing. The forces for thumb and index finger were measured separately, hence grip force values are the average of the grip force of both fingers. We observed that the grip force of thumb and index finger was not the same following the contact with the object. When experiencing a horizontal collision, the finger's position and orientation plays a role in the unloading of the load force onto the fingers. Since the thumb holds a more central position (regarding to the body), one could expect a larger load force unloading onto the thumb. Indeed, we observed grip force profiles with a higher force for the thumb than for the index finger. Together with the fact that the grip force of the thumb followed closely the timing and strength of the load force, we conclude that the mechanical perturbation of the thumb was considerably stronger than for the index finger. The setup did not allow us to control the positioning and orientation of the fingers involved in the precision grip. These observations strengthened our

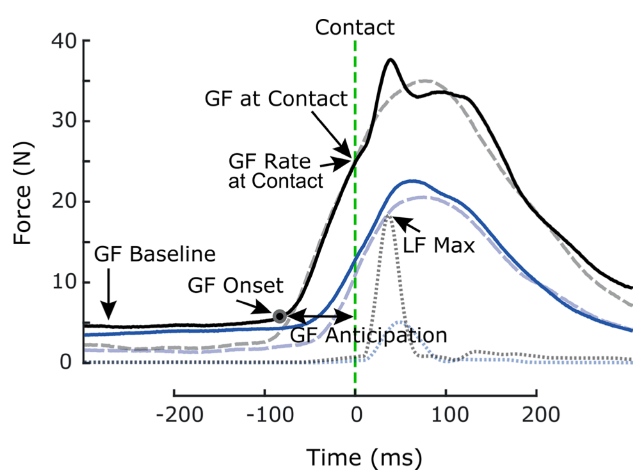


**Fig. 2** Grip and load force profile of soft light (blue) and stiff heavy object (black). Grip force represented by solid (normal trial) and dashed (catch trial) lines. Load force represented by dotted lines. Green dashed line indicates moment of contact with virtual object that was aligned with time zero for all trials. Each line represents a single trial of one example participant

decision to neglect the raw data from the normal trials after contact and to use the pre-collision metrics for predicting the grip force maximum as they were highly correlated (see "Results").

GF at contact is defined as the level of grip force that the participant applied at the handle at the moment of contact. GF rate at contact is the first derivative of the grip force at the moment of contact, calculated as the average rate over the last 10 ms before contact. GF baseline is the average grip force level in between the collisions, calculated over 250 ms, starting from 50 ms before the object started to move to 200 ms after. The onset of the grip force was determined as the first moment at which the grip force exceeds the baseline plus five times the standard deviation of the baseline and remains higher than this threshold for more than 10 ms. GF anticipation was defined as the temporal difference between the grip force onset and the moment of contact.

### Model for predicted grip force maximum

Unfortunately, the grip force traces of the normal trials were mechanically disturbed by the impact loads (see Fig. 2), hence it was not possible to read out the actual grip force maximum applied during the trials. To be able to analyze the grip force maximum of the normal trials, we used multiple regression to estimate the grip force maxima with the help of the undisturbed catch trials.

With the multiple regression on the catch trials, we determined the correlation of the grip force maximum (GFM) with the grip force at contact (GFC) and its first derivative at contact (dGFC/d*t* [F/s]):

$$\mathrm{GFM} = 0.93 \times \mathrm{GFC} + 0.05211 \times \mathrm{dGFC}/\mathrm{d}t,$$

with $R^2 = 0.84$. Both components contribute significantly (both $p < 0.001$). The determined values are similar to the ones found in an active collision task in the study of White et al. (2011). The high correlation between the prediction and the measured grip force maximum in the catch trials shows that we can well predict the level of the grip force maximum based on the GF at contact and the GF rate at contact. We used this predictive model to calculate the predicted GF max for all trials.

We compared the predicted GF max, GF at contact, GF rate at contact, GF baseline and GF anticipation over starting direction, objects and trials with $2 \times 6 \times 6$ repeated measures ANOVA (starting direction × object × trial). When a significant main effect of object was present, a post hoc $3 \times 2$ ANOVA (mass × stiffness) was performed to test the effects of mass and stiffness. In all ANOVAs, Greenhouse–Geisser corrections were used when sphericity was violated, and Bonferroni corrections were used in all post hoc comparisons.

## Results

In this study, participants were asked to hold both handles of a bimanual endpoint manipulandum in a precision grip with custom-made integrated force sensors. In a collision task, the participant was asked to hold the hands at the starting positions while an object collides with one of their static hands. We analyzed force patterns and their timing during the preparation and collisions.

### Grip force

Figure 3 shows the average across participants of four different grip force characteristics for each trial number and each object condition: The predicted grip force maximum (predicted GFmax), the grip force level at the moment of contact (GF at contact), the grip force level between collisions (GF baseline), and the grip force rate at the moment of contact (GF rate at contact). For all four parameters, no difference can be seen for the different objects in the first trial, but a clear distinction for the six different objects can be seen in the later trials. Significant main effects for the trial number and for the interaction between trial number and objects revealed that the grip force behavior changed significantly from trial 1 to trial 6. Furthermore, significant main effects for object mass and object stiffness as well as its interaction were found, meaning that the grip force property was adjusting to each mass and stiffness, respectively. Both a larger mass and a higher stiffness resulted in larger grip force levels and a larger grip force rate at contact. Statistical tests showed no difference regarding the hand used during the first trial, so the data sets of both starting directions were analyzed together. Below, we describe the results on these metrics in more detail.

#### Predicted grip force maximum

The results showed (Fig. 3a) that for the first trial of each block, the level of predicted GFmax was consistent (~ 19 N). Starting from the second trial (which was with the opposite hand), the predicted GFmax diverged based on the characteristics of the objects. For trials 3–6, the predicted GFmax levels were consistent and adjusted to the mass and stiffness of the objects (from ~ 15 N for the light soft object to ~ 22 N for the heavy stiff object).

A $2 \times 6 \times 6$ repeated measures ANOVA (starting direction × object × trial) on the predicted grip force maximum showed no main effect of starting direction ($F_{1.0,18.0} = 2.40$, $p = 0.139$). A main effect of object ($F_{5,90} = 30.42$, $p < 0.001$) showed an effect of the different object characteristics. A post hoc $3 \times 2$ ANOVA (mass × stiffness) showed significant

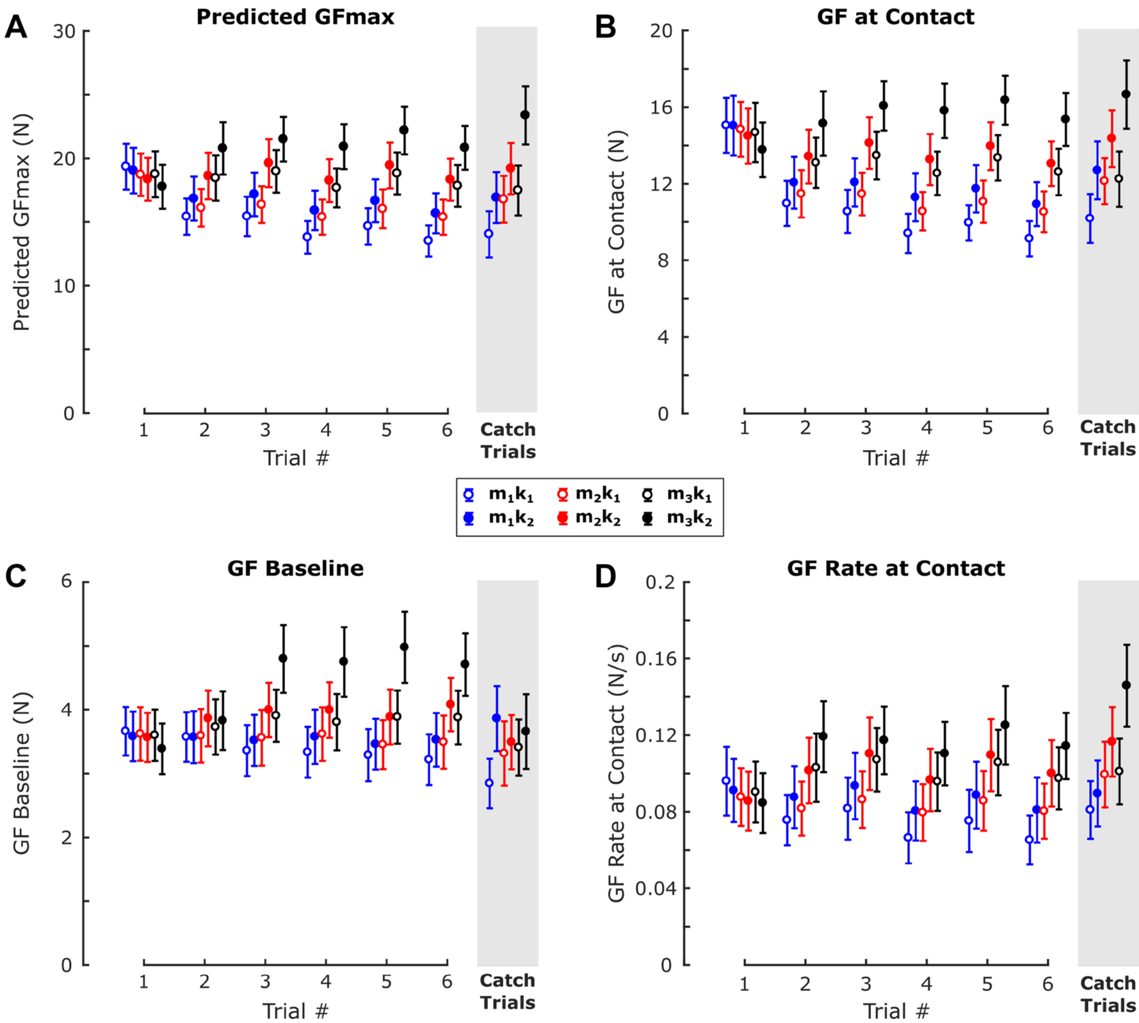


**Fig. 3** Grip force depending on trial and object. Predicted GFmax (**a**), GF at contact (**b**), GF baseline (**c**) and GF rate at contact (**d**) plotted for normal trials 1–6 (group data). The catch trials of trials 2–6 are combined into one data point at the right of each panel. Colors indicate object mass (blue = $m1$, red = $m2$, black = $m3$) and type of circle indicates object stiffness (hollow circle = $k1$, filled circle = $k2$). Error bars indicate SEM

main effects of mass ($F_{2,36} = 57.55$, $p < 0.001$) and stiffness ($F_{1.0,18.0} = 32.26$, $p < 0.001$) and no significant interaction ($F_{2,36} = 0.46$, $p = 0.63$). Both a larger mass and a higher stiffness resulted in larger grip force maxima. A main effect of trials ($F_{1.3,23.9} = 5.30$, $p = 0.022$) and post hoc comparisons with Bonferroni corrections showed a difference between the predicted GFmax for the first trial and the fifth trial ($p = 0.032$). An interaction effect was seen for starting direction × object ($F_{2.4,43.9} = 21.03$, $p < 0.001$), showing more distinct differences in the predicted grip force maximum between the objects when the first collision was to the right hand than when it was to the left hand. An interaction effect was seen for trial × object ($F_{7.3,130.7} = 8.28$, $p < 0.001$), reflecting the difference between the predicted grip force maximum for the first trials and the adjustments based on the object characteristics on the following trials. Also, an interaction effect for starting direction × trial × object ($F_{6.9,124.9} = 6.19$, $p < 0.001$) was found.

### GF at contact

The results showed (Fig. 3b) that for the first trial of each block, the level of grip force at contact was consistent (~ 15 N). Starting from the second trial (which was with the opposite hand), the grip force at the moment of contact diverged based on the characteristics of the objects. For trials 3–6, the grip force levels at contact were consistent and adjusted to the mass and stiffness of the objects (from ~ 10 N for the light soft object to ~ 16 N for the heavy stiff object).

A 2 × 6 × 6 repeated measures ANOVA (starting direction × object × trial) on the grip force at contact showed no main effect of starting direction ($F_{1.0,18.0} = 0.55$, $p = 0.469$).

A main effect of object ($F_{2.1,37.0} = 50.01$, $p < 0.001$) showed an effect of the different object characteristics. A post hoc 3 × 2 ANOVA (mass × stiffness) showed significant main effects of mass ($F_{1.2,21.3} = 79.37$, $p < 0.001$) and stiffness ($F_{1.0,18.0} = 46.22$, $p < 0.001$) and a significant interaction ($F_{2,36} = 3.36$, $p = 0.046$). Both a larger mass and a higher stiffness resulted in larger grip force levels at contact. A main effect of trial number ($F_{1.7,31.4} = 20.45$, $p < 0.001$) and post hoc comparisons with Bonferroni corrections showed a difference between the grip force at contact for the first trial and all other trials (all $p < 0.01$ for comparison with the first trial). Other differences were found between trial 3 and trial 4 ($p = 0.016$), trial 3 and trial 6 ($p = 0.002$), trial 4 and trial 5 ($p = 0.042$), and trial 5 and 6 ($p = 0.001$). An interaction effect was seen for trial × object ($F_{6.8,122.3} = 20.44$, $p < 0.001$), reflecting the difference between the grip force at the first trial and the adjustments on the following trials.

#### GF baseline and GF rate at contact

In addition to the adjustment of the grip force at contact according to mass and stiffness of the virtual objects, both the baseline grip force level in between collisions (GF baseline, Fig. 3c) and the grip force rate at contact (GF rate at contact, Fig. 3d) adjusted as well to virtual object properties.

A 2 × 6 × 6 repeated measures ANOVA (starting direction × object × trial) on GF baseline showed no main effect of starting direction ($F_{1.0,18.0} = 0.02$, $p = 0.893$) but a main effect of object ($F_{1.4,25.2} = 17.30$, $p < 0.001$). A post hoc 3 × 2 ANOVA (mass × stiffness) showed significant main effects of mass ($F_{1.1,21.4} = 23.01$, $p < 0.001$) and stiffness ($F_{1.0,18.0} = 16.34$, $p = 0.001$) and a significant interaction ($F_{1.4,25.9} = 6.75$, $p = 0.008$). Both a larger mass and a higher stiffness resulted in larger GF baseline. A main effect of trial number ($F_{2.7,49.1} = 4.76$, $p = 0.001$) was found, but no post hoc differences. An interaction effect was seen for trial × object ($F_{5.1,91.9} = 13.43$, $p < 0.001$), reflecting the difference between the GF baseline for the first trial and the adjustments based on the object characteristics on the following trials. There was no significant difference for the GF baseline between the first and second collision ($p > 0.77$), from which we could speculate that the GF baseline is apparently not part of the prediction for the impact, but more the result of the experience of the previous collision.

A 2 × 6 × 6 repeated measures ANOVA (starting direction × object × trial) on GF rate at contact showed no main effect of starting direction ($F_{1.0,18.0} = 0.02$, $p = 0.881$) but a main effect of object ($F_{2.3,43.4} = 39.52$, $p < 0.001$). A post hoc 3 × 2 ANOVA (mass × stiffness) showed significant main effects of mass ($F_{1.2,21.3} = 54.80$, $p < 0.001$) and stiffness ($F_{1.0,18.0} = 34.19$, $p < 0.001$) and a significant interaction ($F_{2,36} = 3.63$, $p = 0.037$). Both a larger mass and a higher stiffness resulted in a larger GF rate. A main effect of trial number ($F_{2.3,40.9} = 5.17$, $p = 0.008$) was found, with post hoc comparison patterns similar to those for GF at contact. An interaction effect was seen for trial × object ($F_{5.6,101.3} = 10.02$, $p < 0.001$), reflecting the difference between the grip force rate at contact for the first trials and the adjustments based on the object characteristics on the following trials.

### Catch trials

The results of the catch trials were overall very similar to the normal trials (see catch trials in Fig. 3). It is difficult to statistically test these findings in a scientifically sound way, since there is only limited data on the catch trials on each position in the sequence and we see clear effects of the sequence on the normal trials. However, testing the catch trial data to the overall mean of the normal trials for each object did not show any significant differences in any of the metrics before or at the (predicted) moment of impact (all $p > 0.3$). Being similar to the normal trials before and at contact (e.g., GF at contact, GF baseline, GF rate at contact) illustrates that the participants could not predict whether a trial was a catch trial or not. Since there were no collisions for the catch trials, the measured grip force profiles gave us insight into the motor planning and anticipation for the whole trial without the mechanical perturbations of the actual collision (see "Methods" for the calculation of a predicted grip force maximum for the normal trials). The grip force profiles of the catch trials showed that the value of the grip force at contact is not the maximum grip force, but this maximum is reached later [similar as in White et al. (2011)]. Pooled catch trials of all participants showed that the grip force maximum is 82 ± 39 ms after the contact (not shown) and that it did not depend on the object characteristics.

### Grip force timing

In contrast with the grip force levels that nicely adjusted to the virtual objects' mass and stiffness, we found that the grip force onset in anticipation of the object contact (GF anticipation) and the following collision was constant and also independent of the object characteristics. The following results suggest therefore an object-independent temporal grip force planning.

#### GF anticipation

To see whether the adjusted grip force levels originated from the timing of the anticipation, we compared the moment of grip force onset, i.e., the moment in time at which the grip force exceeds five times the standard deviation of the baseline grip force level, for each trial. The temporal anticipation (Fig. 4) was longer for the first trial (~ 170 ms) compared

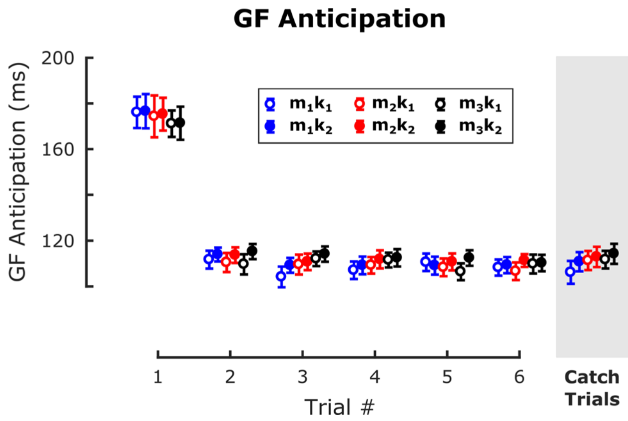


**Fig. 4** Grip force anticipation (group data) plotted for normal trials 1–6 and catch trials. The catch trials of trial numbers 2–6 are combined into one data point at the right of the panel. Colors indicate object mass (blue = $m1$, red = $m2$, black = $m3$) and type of symbol indicates object stiffness (hollow circle = $k1$, filled circle = $k2$). Error bars indicate SEM

to the following trials (~ 110 ms) but did not depend on the characteristics of the objects.

Like for the GF levels, a 2 × 6 × 6 repeated measures ANOVA (starting direction × object × trial) on the temporal anticipation showed no main effect of starting direction ($F_{1.0,18.0} = 0.34$, $p = 0.566$). In contrast to the GF levels, it did not show a main effect of object ($F_{5,90} = 1.43$, $p = 0.221$). A main effect of trial number ($F_{1.4,24.9} = 160.86$, $p < 0.001$) and post hoc comparisons with Bonferroni corrections showed a difference between the temporal anticipation for the first trial and all other trials (all $p < 0.001$ for comparison with the first trial, all other comparisons had $p > 0.268$).

### Grip force timing in catch trials

To further explore the timing in the grip force planning, we performed additional analyses on the catch trials. As described above, the grip force maximum was not at the moment of contact, but 82 ± 39 ms after the moment of contact [similar to White et al. (2011)] and this timing did not depend on the object characteristics. These constant temporal factors are especially noteworthy given the fact that the time between contact and load force peaks differs considerably (as seen in Fig. 2) with a difference over 40 ms between the light stiff object ($m1k2$, 27 ms after contact) and the heavy soft object ($m3k1$, 69 ms after contact).

## Discussion

In this study, we investigated the preparation of the grip force response to counteract six different impact loads that differed in mass and stiffness. Participants encountered each type of impact load in sequences of six collisions. We studied the force levels and the timing of the grip behavior to learn more about the grip force motor planning strategies.

First, the results showed that one single collision is sufficient to get enough information to prepare for the next collision, even when this collision is to the other hand. This process whereby training with one limb leads to subsequent improvement in performance by the contralateral untrained limb is called cross-education (e.g., Ruddy and Carson 2013). It has been found that cross-education can increase the strength of the untrained contralateral limb when training the other.

Next, we found that grip force levels, both pre- and post-collision, adjust very well to the object characteristics. Grip force at contact and grip force rate was nicely adjusted to mass and stiffness. Due to the mechanical disturbance of the grip force after contact, we could not directly measure the grip force maximum in the normal trials, but from the catch trials we learned that the level of the GF maximum can be very well predicted from the GF at contact and the GF rate at contact. This prediction was very similar to the prediction made by White et al. (2011) in their study with vertical active collisions.

Looking at the timing of the grip force preparation, there were no differences in the temporal profile for the different object characteristics, but we observed a significantly longer anticipation time for the first trial of every block. The first trial of each block differed in two ways from the subsequent repetitions. On one hand, the mass and the stiffness were unknown to the participant during the first trial so that this uncertainty could have led to an earlier rise in the grip force. On the other hand, the time between when the object was displayed and started moving was 2300 ms during the first trial and only 50 ms during the subsequent trials of each block. Therefore, the time between the initial object's appearance and the object's contact with the participant's hand was also considerably shorter, so that the shorter available time until contact could have led to an overall shorter anticipation time for the subsequent trials of each block. A follow-up study could bring clarity to the question whether a different timing of the object presentation does indeed influence the anticipation time.

Strikingly, our results revealed that the temporal onset of the grip force build up does not depend on the impact load, so that participants avoid slippage by exclusively adjusting the other grip force characteristics (e.g., grip force level and rate). Also, we found that the timing of the grip force peak does not depend on the impact load either [similar to White et al. (2011)], which suggests an altogether time-locked planning of the grip force profile.

Time-locked motor planning has also been found in other motor tasks. For example, Lefèvre et al. (1992) showed that a fixed period of time (~ 40 ms) is needed to restore an inhibited vestibulo-ocular reflex at the end of large amplitude gaze shifts. The authors suggested that the gaze control system is using a predictive strategy based on the knowledge of head velocity and instantaneous gaze motor error. McIntyre et al. (2001) also showed a fixed timing of an action movement (catching a falling ball) in their experiments with different gravity conditions (1 g and 0 g). The authors found that in 1 g participants started their muscle activity to catch the ball 200 ms before contact, and this was independent of the ball velocity and the height of the release of the ball. In an untrained 0 g condition, the peak of the anticipatory motor response was found to be earlier (with respect to the moment of contact), suggesting that the timing shifted because of a mismatch in perceived moment of contact. After repeated exposure, the perceived moment of contact and with that the initiation of the motor action shifted (though not completely) towards the findings in 1 g. The time-locked motor planning relative to the time to contact appears similar to our results where the grip force onset in preparation for the collision is time locked and independent of object mass and stiffness.

Visual information plays a critical role when estimating the time to contact in many daily tasks. On one hand, the visual system can use the motion of the visual image on the surface of the retina (retinal slip), e.g., while driving on the highway when a car is cutting your lane or in the case of looming when the retinal image becomes increasingly large so that it is perceived as an approaching object (e.g., Gibson 2014). Hereby, timing is limited by the response latencies of the photoreceptor (Kietzman and Sutton 1968) and the dependency on luminance, color, and contrast of the signal processing latencies in different brain areas (e.g., Thompson 1982). On the other hand, if sufficient time is available, humans can pursue the visual stimulus (Brenner and Smeets 2009, 2011), so that the target's position and velocity are derived from (continuous) oculomotor signals rather than from (intermittent) retinal signals. Accordingly, temporal precision is poorer when the moving target is not visually pursued (Brenner and Smeets 2011). At a neural level, recent studies about the neural coding of the motor system show that precise timing can be achieved by the millisecond-scale timing patterns of action potentials (spike timing) in addition to the already established total number of spikes fired within a specified time interval (spike rate) (Srivastava et al. 2017; Sober et al. 2018). This could explain why estimating the time to contact of a collision in our task can be very precise enabling exact temporal motor planning.

Further preferences for time-locked motor planning have been observed in interception. Brenner and Smeets (2015) presented an interception study, in which performance was found to be better when the timing of the reaching movement was fixed, and the point of interception was fine-tuned by the participants than when the timing needed to be fine-tuned to reach a precise position for the interception. They argue that the reason for this improved precision is a shorter feedback delay for updating the anticipated point of interception with a fixed timing than for updating the anticipated time of interception for a fixed point. This is in line with an earlier study (Brenner et al. 1998) where changing the timing of an interception takes longer than changing the position. Consequently, Brenner and Smeets (2015) propose that people use time-locked motor planning to achieve the amazing precision that is reported for several sports situations (Bootsma and van Wieringen 1990; Mcleod and Jenkins 1991; Regan 1992).

A follow-up study could explore whether the time-locked motor control is an essential part of the grip force motor planning by testing participant's specific brain regions. Both motor timing and time perception underlie similar cerebral structures as revealed by a FMRI study (Schubotz et al. 2000) which is often identified as the cerebellum in other studies. Hence, impaired sensorimotor timing was found in adults with attention-deficit/hyperactivity disorder due to an atypical function of the cortico-cerebellar system (Valera et al. 2010) and the associated degeneration of the cerebellum in patients with spinocerebellar ataxia led to quantitative deficits in temporal processing for predictive motor timing (Bares et al. 2011). Testing patients with these conditions could clarify the reliance on the time-locked behavior. In the reverse case, our task might be used as a clinical test to assess the severity or the evolution of pathologies affecting timing and motor control as observed, e.g., in Parkinson patients [for a review see Lucas et al. (2013)].

Furthermore, it would be interesting to see whether a constant timing is preserved in active collisions, namely when a certain force has to be transmitted to a stationary object by colliding a hand-held object with it. During active collisions, an efferent copy of the arm movement is available, which might influence the perceived time to contact. This could shed some light on the extent to which the central nervous system takes self-motion into account and how it adapts the timing of the grip force motor planning.

To conclude, in this study, we not only confirmed that grip force levels adjust to the mass and stiffness of the colliding object but also showed that this adjustment is transferred to the other hand after one single collision. Moreover, our findings reveal a grip force onset that is independent of the collision characteristics and suggest that the complete timing of the grip force profile is time locked.

**Acknowledgements** The authors would like to thank Laurane Guiot, for her help to collect the data and design the protocol, as well as the participants of this study for their kind participation in this time- and energy-consuming experiment. This research was supported by a Rubicon Grant (446-17-003) from the Netherlands Organization of Scientific Research (NWO) (to IAK), by a Grant from the European

Space Agency, ARC (Actions de Recherche Concertée), Prodex, and IAP VII/19 DYSCO (BELSPO, Belgian Federal Government).

## Compliance with ethical standards

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

## References

Bares M, Lungu OV, Liu T, Waechter T, Gomez CM, Ashe J (2011) The neural substrate of predictive motor timing in spinocerebellar ataxia. Cerebellum 10:233–244

Bleyenheuft Y, Lefevre P, Thonnard J-L (2009) Predictive mechanisms control grip force after impact in self-triggered perturbations. J Mot Behav 41:411–417

Bootsma RJ, van Wieringen PC (1990) Timing an attacking forehand drive in table tennis. J Exp Psychol Hum Percept Perform 16:21

Brenner E, Smeets JB (2009) Sources of variability in interceptive movements. Exp Brain Res 195:117–133

Brenner E, Smeets JB (2011) Continuous visual control of interception. Hum Mov Sci 30:475–494

Brenner E, Smeets JB (2015) How people achieve their amazing temporal precision in interception. J Vis 15:8

Brenner E, Smeets JB, de Lussanet MH (1998) Hitting moving targets continuous control of the acceleration of the hand on the basis of the target's velocity. Exp Brain Res 122:467–474

Delevoye-Turrell Y, Giersch A, Danion J-M (2003) Abnormal sequencing of motor actions in patients with schizophrenia: evidence from grip force adjustments during object manipulation. Am J Psychiatry 160:134–141

Flanagan JR, Tresilian JR (1994) Grip-load force coupling: a general control strategy for transporting objects. J Exp Psychol Hum Percept Perform 20:944

Flanagan JR, Wing AM (1993) Modulation of grip force with load force during point-to-point arm movements. Exp Brain Res 95:131–143

Flanagan JR, Wing AM (1997) The role of internal models in motion planning and control: evidence from grip force adjustments during movements of hand-held loads. J Neurosci 17:1519–1528

Gibson JJ (2014) The ecological approach to visual perception, classic edn. Psychology Press, London

Johansson R, Westling G (1988) Programmed and triggered actions to rapid load changes during precision grip. Exp Brain Res 71:72–86

Kietzman ML, Sutton S (1968) The interpretation of two-pulse measures of temporal resolution in vision. Vis Res 8:287–302

Lefèvre P, Bottemanne I, Roucoux A (1992) Experimental study and modeling of vestibulo-ocular reflex modulation during large shifts of gaze in humans. Exp Brain Res 91:496–508

Lucas M, Chaves F, Teixeira S, Carvalho D, Peressutti C, Bittencourt J, Velasques B, Menéndez-González M, Cagy M, Piedade R (2013) Time perception impairs sensory-motor integration in Parkinson's disease. Int Arch Med 6:39

McIntyre J, Zago M, Berthoz A, Lacquaniti F (2001) Does the brain model Newton's laws? Nat Neurosci 4(7):693

Mcleod P, Jenkins S (1991) Timing accuracy and decision time in high-speed ball games. Int J Sport Psychol 22:279–295

Nowak DA, Hermsdörfer J (2006) Predictive and reactive control of grasping forces: on the role of the basal ganglia and sensory feedback. Exp Brain Res 173:650–660

Nowak DA, Glasauer S, Hermsdörfer J (2004) How predictive is grip force control in the complete absence of somatosensory feedback? Brain 127:182–192

Regan D (1992) Visual judgements and misjudgements in cricket, and the art of flight. Perception 21:91–115

Ruddy KL, Carson RG (2013) Neural pathways mediating cross education of motor function. Front Hum Neurosci 7:397

Schubotz RI, Friederici AD, Von Cramon DY (2000) Time perception and motor timing: a common cortical and subcortical basis revealed by fMRI. Neuroimage 11:1–12

Serrien D, Kaluzny P, Wicki U, Wiesendanger M (1999) Grip force adjustments induced by predictable load perturbations during a manipulative task. Exp Brain Res 124:100–106

Sober SJ, Sponberg S, Nemenman I, Ting LH (2018) Millisecond spike timing codes for motor control. Trends Neurosci 41:644–648

Srivastava KH, Holmes CM, Vellema M, Pack AR, Elemans CP, Nemenman I, Sober SJ (2017) Motor control by precisely timed spike patterns. Proc Natl Acad Sci 114:1171–1176

Thompson P (1982) Perceived rate of movement depends on contrast. Vis Res 22:377–380

Turrell YN, Li F-X, Wing A (1999) Grip force dynamics in the approach to a collision. Exp Brain Res 128:86–91

Valera EM, Spencer RM, Zeffiro TA, Makris N, Spencer TJ, Faraone SV, Biederman J, Seidman LJ (2010) Neural substrates of impaired sensorimotor timing in adult attention-deficit/hyperactivity disorder. Biol Psychiat 68:359–367

White O, Thonnard J-L, Wing A, Bracewell R, Diedrichsen J, Lefèvre P (2011) Grip force regulates hand impedance to optimize object stability in high impact loads. Neuroscience 189:269–276