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FULL PAPER

The Role Of Quantitative Information About Slip And Grip Force In Prosthetic Grasp Stability

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Prosthetic hands introduce an artificial sensorimotor interface between the prosthesis wearer and the environment, that is prone to perturbations. We analyze theoretically and evaluate psychophysically the performance in stable grip control in conditions of physical grasps perturbation, such as object slip. Simulation results suggest that user-centered stable grasp control depends on two primal user parameters: reaction time to slip and grip force intensity. Experiments with human users indicate that a user's response time can be controlled by relaying information about the speed of the slipping object, while minimal grip force intensity can be adjusted with information about grip force at the onset of the slip. Based on our theoretical and experimental findings, we propose a stable grasp control method for prosthetic hands.

Keywords: slip, upper-limb prosthetics, grasp stability, tactile sensor

1. Introduction

Stability in grasping is attributed to a sensorimotor system that is able to transform information about grasp forces in the human hand in order to ensure adequate safety margins against slip [1]. As an object is grasped, grip forces must be regulated in such a way that slip or excessive forces are avoided. Johansson and Cole [1] advocate that grasp stability in adults relies not only on predictive models in the central nervous system (CNS), but also on the sensory-driven control of discrete events. While the former control scheme characterizes predictable grasp attributes that are part of formed models in the CNS, e.g., object weight, frictional coefficients, the latter characterizes unanticipated events that threaten the stability of the grasp, e.g., passive slip.

Prosthetic hands introduce an engineered sensorimotor interface that impedes the natural reliance on neural predictive models and that is prone to generating significant perturbations during grasp. As such, slip and excessive forces applied on manipulated objects are common across prosthetic hand wearers [2, 3]. In such scenarios, the prosthesis wearer is challenged to re-learn or overwrite the previous models by a sensorimotor transformation adapted to the prosthesis in order to grasp stably. The acquisition of an updated grasp control model claims a new developmental process highly dependent on incoming sensory information and practice.

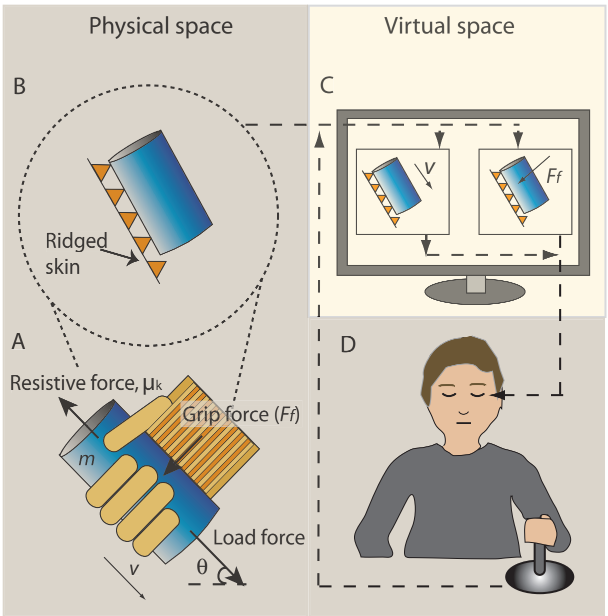

Figure 1. Schematics of the experimental grasp loop. A. Robot hand on which an object of mass m slips with speed v. B. Detail of the object slipping on an artificial ridged skin that is mounted on the robot hand. C. Screen showing graphical information about object's slip speed (v) or user grip force (F_f) to the participant. D. Participant controls grasp via a joystick.

2. Related work

In a user-oriented approach, central to the sensorimotor grasp processes are the transmission of the sensing information about robot hand-object interaction to the user and the motor response of the user. Mapping the environmental information to prosthesis wearers has been commonly achieved through the tactile display of grip forces on to the human skin by various haptic technologies, e.g., [4] [5] [6–8]. Although this type of force feedback can characterize the grip force intensity, it cannot solely guide toward grasp stability through an untrained artificial interface in a real-world scenario. This deficiency mainly stems from the inability to transmit whether grip force is insufficient (object slips), efficient or economical (object is stable in the hand) or excessive (object is overpressed), and thus cannot exclusively guide a user's response. There is physiologic evidence that grasp stability in an upper-limb prosthesis may not depend only on relaying information about grip force [1] [9]. According to these studies, slip is a pivotal determinant in grip control. Grasp in virtual reality with a tactile slip and force display was investigated in [10, 11]. The studies found that slip and force feedback assist user participants better than force feedback alone in a stable manipulation of a virtual object with lower forces. For tele-manipulation, Edin et al. [12] devised an instrumented object that transmits frictional information through mounted solenoids and elicits physiological responses that resemble the responses observed during slips, such as an increase in a user's grip force. Li et al. [13] displayed grasp information by vibrations for patients with multiple sclerosis in order to help them manipulate objects more efficiently. This methodology consisted of relaying amplitude-based feedback proportional to the grip force, or event-cue vibration feedback, which alerted users when their grip force strayed from a safe-grasp force range. Under these conditions, patients could grasp and lift objects more successfully than they could without any feedback. Although slip role on grasp stability has been clearly found in physiological studies with humans, there has been limited investigation about the contribution of slip information in user-in-the-loop prosthetic applications. Although the scientific findings of these few haptics approaches are highly valuable, they are mostly appropriate for rehabilitation training because the haptic

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slip feedback is virtually produced or physically confined to a limited set of objects with known coefficients of friction.

In hand prosthetics, stable grasp is most challenging due to unpredictable characteristics of the robot hand-object interface. In this case, slip is physically produced under diverse and uncontrollable conditions. Recently, the potential of relaying quantitative slip information for grasp stability has been advocated. A prime indicator that the rate of slip may influence the grip response appears in [1]. Slip that is artificially generated by changing the load force on an object held in the human hand was found to improve the agility of the grip response, which depended on the load force rate. In a more comprehensive study of slip speed effects for hand prostheses, slip speed feedback improved the promptness to overcome slip and led to more economical and less variable user response [14].

In this study, we reveal the role of quantitative information about slip and grip force on grasp stability with user in the loop with the general aim to impact on the design of feedback interfaces for effective grasp with hand prosthetic systems. Specifically, this investigation directly informs the advancement of the prosthetic system, tactile sensors, and a haptic device developed by our group [15–17]. The study is thus twofold, investigating the effectiveness of the feedback loop of the prosthetic system in the presence of two factors: (1) quantitative information regarding two grasp cues (force, slip) and (2) noise from the artificial sensing. We pursue our investigation using minimal and realistic conditions (see Fig. 1). First, feedback to the users is provided visually, via a graphical interface, taking advantage of the simple existing experimental platform. Second, our tactile sensors [15] are being used to factor in possible signal noise that users may experience in real scenarios of grasp instability.

Our theoretical considerations indicate that within a user-centered approach, reaction time and grip force intensity need to be controlled in order to avoid grasp instabilities such as slip and excessive force. This work proposes, through psychophysical experiments, that information about slip speed can regulate reaction time to grip, while information about grip force just above the one corresponding to the onset of the slip (slip margin) can control an economical grip force. These two types of information may provide a minimal yet comprehensive sensorimotor representation for achieving stable grasp. We finally propose a guiding scheme to achieve grasp stability in prosthetic applications.

This study uses visual feedback to simulate grasp events, yet a more natural feedback is via haptic transfer. Although studies have identified a high degree of equivalence between the visual and haptic modality perception especially for simple static and dynamic information [18, 19], there exists no particular study to demonstrate the congruence of visual and touch feedback pertaining to the type of information relayed here. Nonetheless, we used two intuitive types of visual information to represent slip speed and force intensity, and thus an analogy to the haptic stimulation could be formulated. For example, an analogous haptic feedback has been proposed, yet not integrated in this system, in [17, 20], where slip speed and force intensity were relayed as a sweep and tap on the skin, and the users were able to discriminate qualitatively at least four levels of each type of haptic stimulation.

3. User-centered grasp model

3.1. *Model*

Grasp with prosthetic hands involves the study of the interaction between an object and a robot hand as a passive element, e.g., palm on which the object resides, and as an active element, e.g., fingers, which regulate grip forces. There are numerous models developed for grasp control, e.g., [21] [22], with a review in [23, 24]. Most of these models are focused on analytical solutions for automatic grasp envisaging automatic robot hands relying on their high bandwidth and ca-

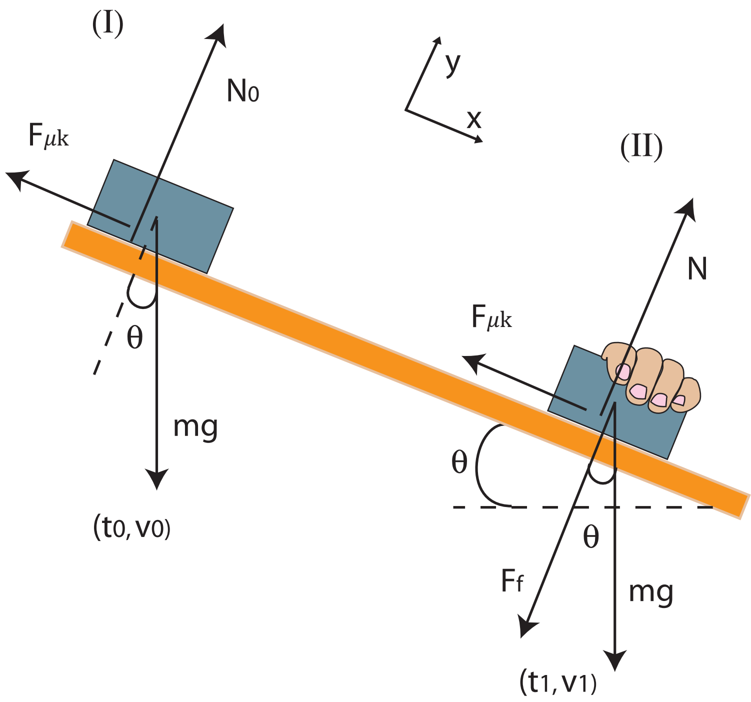

Figure 2. Model of forces acting on a slipping object (I) in free slip and (II) under grip force conditions.

pability of high computational power [25]. These models are also constructed in association with technological solutions in tactile sensors. Slip has been detected by the computation of the coefficient of friction using multi-dimensional sensors [26–28], changes in contact forces across arrays of sensors [29–33], or vibrations in tactile sensors [34–37]. Some work also investigates slip and stick phenomenon for slip detection [38, 39], although this model is limited to implementation of multi-dimensional sensors, and is challenging in real scenarios. Although these models may be closest to how slip is perceived in humans, their success in real scenarios is yet to be demonstrated. Furthermore, these models do not view grasp as a user-oriented time-dependent process. Amputee-robotic interfaces are bandwidth-limited, and communicating the right information to the user could optimize the use of the prosthesis resources. In our setup we have one sensor that can be used for both force sensing and slip due to the ridged surface, whose advantages have been broadly explored in [40]. Additionally, instead of considering incipient slip, we consider gross slip, which is the worst scenario.

In our study, we considered a time-related user-centered grasp model in which we investigated how the user can affect grasp. In Fig. 2, an object is situated on an inclined surface representing the palm of a robotic hand, on which it can slide. If the object starts slipping (case I), it results that

$$\ddot{x} = g \sin\theta - \mu_k g \cos\theta \tag{1}$$

where μ_k is the coefficient of kinetic friction, g is the gravitational acceleration, θ is the angle between the inclined surface and the horizontal axis. Case II illustrates the case when active contact, e.g., fingers, is made with the object at time t_1 in order to voluntarily stop the slip. Thus:

$$\ddot{x} = g \sin\theta - \mu_k(\frac{F_f}{m} + g \cos\theta), \tag{2}$$

where m is the mass of the slipping object, and F_f is the grip force applied through active contact.

We can determine when the object is stopped ($t = t_S$):

$$t_S = t_1 - \frac{v_1}{g\sin\theta - \mu_k(\frac{F_f}{m} + g\cos\theta)} \quad (3)$$

$$= t_1 \frac{-\mu_k \frac{F_f}{m}}{g\sin\theta - \mu_k(\frac{F_f}{m} + g\cos\theta)}, \quad (4)$$

where v_1 is the object's speed at the time of the active contact, t_1. Equation 3 was obtained by integrating Eq. 2 and computing the speed at time t_1, while Eq. 4 was derived by integrating Eq. 1 at time t_1 for which

$$v_1 = (g\sin\theta - \mu_k g\cos\theta)t_1. \quad (5)$$

Relations 4 and 5 indicate a linear relation between the time to stop slip and the user's reaction time, and between the slip speed of the object and the user's reaction time, respectively. Here, we assumed that F_f is constant, because the time interval (t_1, t_S) is short.

If slip does not occur due to sufficient grip forces, the state of the object is described by the following relation:

$$\ddot{x} = g\sin\theta - \mu_s(\frac{F_f}{m} + g\cos\theta). \quad (6)$$

Given that the object is maintained in the hand,

$$F_f \geqslant (\frac{\sin\theta}{\mu_s} - \cos\theta)mg, \quad (7)$$

which expresses the grip force intensity as being proportional to the weight of the object. Broadly, F_f can vary in time, with values possibly reflecting excessive forces.

According to Eq. 4, two prominent user-centered parameters responsible for overcoming slip are user grip force, F_f, and response time, t_1. At the same time, grip force is also significantly affected by the mass of the object, e.g., Eq. 7. Figure 3 shows graphically the time to stop the object from slip, t_S, depending on user grip force, F_f (Fig. 3A), and depending on object's mass (Fig. 3B), for a range of user response times between 0.15 and 10 s with a discrete step of 0.5 s. The response time in the figures is represented in colors, as dark blue for quickest response time and dark red for slowest response time. In Fig. 3A, the grip force was considered between 0 and 10 N with a discrete step of 1 N, while the object's mass was fixed to 1 kg. In Fig. 3B, the object's mass varied between 0.2 and 1 kg with a discrete step of 0.2 kg, while the grip force was fixed to 1 N. In addition, we considered $\mu_k = 0.92$ and assumed the palm inclination constant, $\theta = 45°$. Under these conditions, the object's slip speed reaches up to approximately 10 mm/s. For speeds higher than this value, Eq. 4 is fulfilled for increasing grip forces. Figure 3A suggests that the time to stop the slip increases nonlinearly with decreasing grip force and increasing user response time. Inversely, Fig. 3B shows that the time to stop the slip becomes nonlinearly longer with increased object mass and user response time.

3.2. *Model's implication for grasp control*

According to the derived model, two main user-oriented parameters that control the grasp under slip conditions at a specific palm inclination are the user's response time to slip and exerted grip force. Ergonomic factors such as angle of the hand's palm, θ, or physical properties such as object

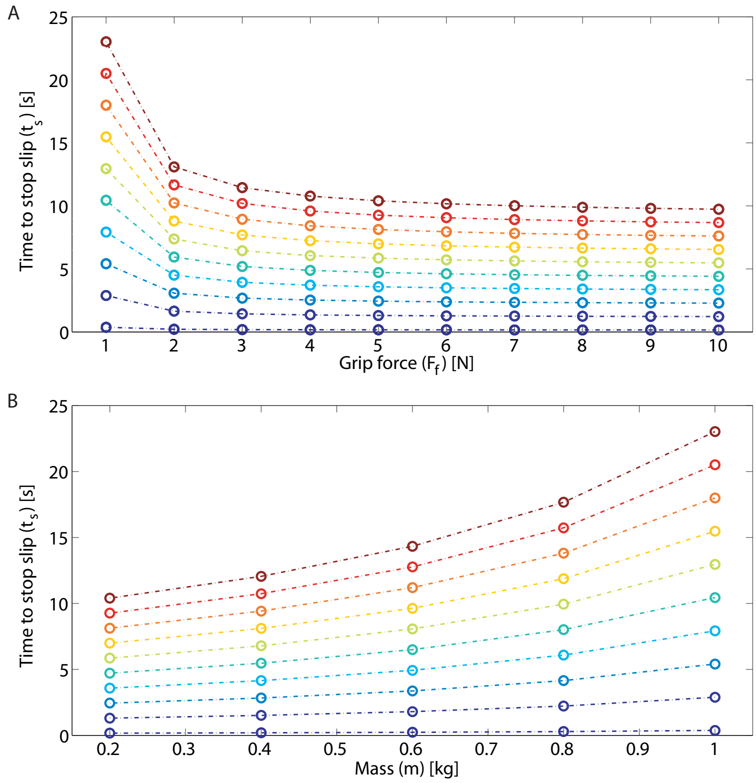

Figure 3. Theoretical time to stop slip. A. Time to stop slip as a function of user grip force and reaction time. The mass was fixed to 1 kg. B. Time to stop slip depending on object's mass and user's reaction time. The grip force was fixed to 1 N. The colors indicate the response time of the user. In this simulation, the quickest response time is represented in dark blue and the slowest response time is represented in dark red.

mass, m, and coefficient of kinetic friction, μ_k, are difficult to determine at the interface between a prosthetic hand and the held object, either by a user or automatically, or come with expensive technological solutions as argued in Section 3.1.

This model of slip, which considers the human in the loop, thus, indicates that the user's grip force should increase and response time to slip should decrease in order to reduce the speed of the object and to stop the slip in a short time. At the same time, fine adjustments on the grip force intensity need to be made because a large grip force is likely to lead to unnecessary energy use or to destroying the held object. In addition, impulsive (short) response time can also hinder the ability of precise grip force adjustments and lead to grip force overshooting. An impulsive response time is likely to occur mainly in situations when the user is not informed of the slip speed of the object; thus the user is not aware of the level of alert he or she should have for stabilizing the slipping object. A similar situation appears in traffic, in which a driver's reaction time to apply the breaks to the car at a traffic light is inversely proportional to the speed of the car [41].

Consequently, we hypothesize that feedback quantities such as an object's slip speed and exerted user grip force can comprehensively contribute to assisting the user's response towards finding the appropriate grip force adjustments. From a technological standpoint, it is also feasible to determine these quantities, because there exists a number of approaches to normal and shear force sensors [42]. In the next sections, we show that the user can control response time and grip force by transmitting information about the slip speed of the object and grip force corresponding to the slip margin, respectively.

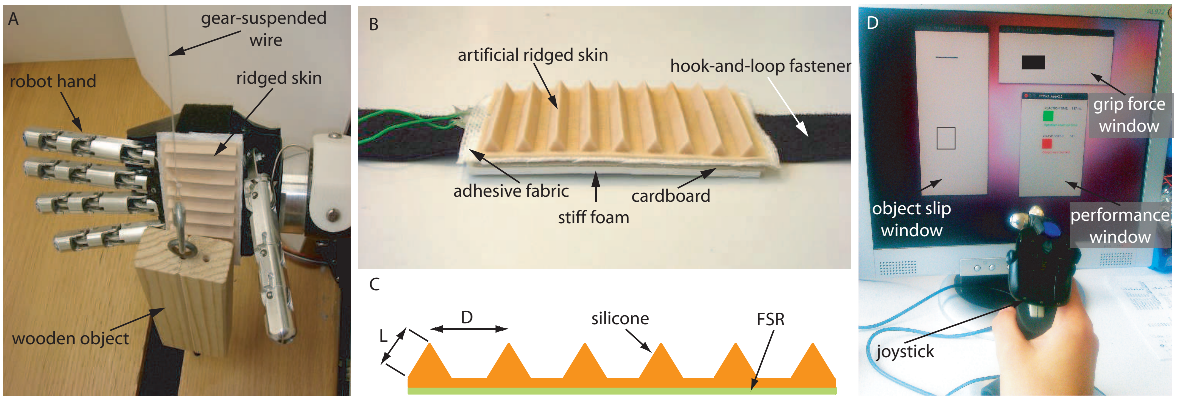

Figure 4. Elements of the experimental setup. A. Artificial ridged skin mounted on a robot hand. A wooden object slides on the skin. B Artificial ridged skin. C. Schematics of the artificial ridged skin illustrating the main components. The triangular side $L = 6$ mm and the inter-ridge distance $D = 10$ mm. D. Screen showing feedback guidance and performance feedback.

4. Materials and methods

4.1. *Experimental setup*

The schematics of the experimental setup are depicted in Fig. 1. An object's slip speed and a user's grip force information related to the grasp of a slipping object on an artificial skin mounted on a robot hand are displayed virtually to a user that controls the grasp through a joystick. The main components of the experimental setup are shown in Fig. 4. A robot hand (specifications in [43, 44]) was fixed on a wooden frame such that its palm was at an angle of 45° with respect to the floor of the frame (Fig. 4A). The robot hand was used as a ramp surface for the slipping object and was not actuated during experiments in order to avoid factors that do not contribute to testing our hypothesis. The robot hand was equipped with an artificial ridged skin (Fig. 4B) whose design and functionality are a simplified version of the skins described in [40, 45]. The artificial skin was built using a two-compound silicone, Neukasil RTV 28 and Neukasil binder A140 (Swiss-Composite). The resulting silicone paste was solidified into a 3D mask built by rapid prototyping. The artificial skin featured uniformly distributed ridges that are 10 mm apart. The transversal shape of the ridge is an equilateral triangle with a side of 6 mm (Fig. 4C). The artificial ridged skin had a length of 90 mm and width of 40 mm, suitable for the robot hand's palm. Underneath the silicone patch, one single force sensor, FSR (Interlink Electronics), acquired the contact force values as the object slid over the ridges. The signals from the FSR sensor were collected by a DAQ system (National Instruments) at 400 Hz and input to a PC running Ubuntu OS for real-time processing.

A wooden rectangular object of size $170 \times 50 \times 25$ mm was used as the sliding object. Its weight was regulated by adding external calibrated weights attached to the bottom of the wooden object. The two calibrated weights were 0.2 and 1 kg. A DC motor (Faulhaber DC-Micromotor 2642) mounted on the wooden frame was set to output a constant rotation speed. A pulley on the motor shaft was connected to the object through a non-stretchable wire that was unwound as the object slid on the artificial skin. The open-loop control of the motor was achieved through a Titech SH2 board (Hibot).

Seven unimpaired volunteers ranging in age from 23 to 35 years participated in the experiments. The participants were seated in a chair in front of a computer monitor. The robot hand setup was placed at their left side and was not visible to them. Information about an object's slip speed or the user's grip force was displayed graphically on the computer screen (Fig. 4D). Participants could exert grasp control by manipulating one degree of freedom of a joystick (Saitek Cyborg EVO) with their dominant hand. They were also deprived of environmental noise by wearing headphones during the experiment. Although a more natural setup, closer to real scenario, would be an active hand control and a haptic interface, the current study focuses on the effect of physically-generated information on the user. In this study, the graphical interface encodes this feedback information that would otherwise be transmitted by a haptic device [17].

4.2. *Experimental procedure*

Prior to commencing the study, ethical clearance was provided by the Swiss Ethics Committee. Participants read the instructions and gave their consent. The task of the participant was to stabilize a slipping object in the robot hand; that is, to stop the slip of an object and to apply a minimal and safe grip force. At the beginning of experiments, the stable grip force was defined for each weight of the experimental object relative to the robot hand. Consequently, the value of the joystick displacement that corresponded to the onset of slip, T_g, was calibrated. As such, for the wooden object to which a mass of 0.2 kg was attached, the joystick displacement that corresponded to the defined onset of slip was $T_g = 570$, which corresponded to a grip force $F_f = 0.65$ N according to Eq. 7. $T_g = 640$ for the same object to which a mass of 1 kg was attached, and corresponded to a grip force $F_f = 3.26$ N. The object started to slip for joystick displacements below the threshold T_g. An offset of 1.8 N (approximately the average between the two minimum expected grip forces for the two weights) was set to be the value beyond which we designate the force as excessive. Consequently, the stable grip force was defined as the interval between the experimental threshold, T_g, and this offset, $T_g + 1.8$ N.

For each new experiment, a calibrated weight of either 0.2 or 1 kg was attached to the wooden object. Within an experimental session, the object slid over the artificial ridged skin at one constant speed. The object's speed was set to 10, 30 or 50 mm/s. The slip speed was randomly selected at the beginning of each session. The participants were relayed guidance information about the object's slip speed or the user's grip force through a graphical interface. Participants could virtually increase the grip by pulling the handle of the joystick from the neutral position toward the user. By pressing a button on the joystick, they confirmed the value of the grip force which they decided suitable to stop slip. The final displacement of the joystick's handle was linearly mapped to the grip force exerted by the user on the slipping object. The effect of the grip force, as exerted through the joystick, was virtual, in that the object was not physically grasped by the robot hand. Thus, the user's grip force input had no immediate consequence on the speed or inertia of the object.

Twenty-four such sessions (3 speeds $\times$ 8 sessions) represented one experiment. A total of three experiments were conducted, in which participants were relayed with three distinct feedback guidances: object slip speed guidance or user grip force guidance or both. The graphical interface included guidance information for grasp during sessions, as well as information about user's performance at the end of each session:

4.2.1. Slip speed guidance

Slip speed guidance was displayed on the user's screen, based on the slip speed of the object as calculated from the force sensor of the robot hand. The force signal from the artificial skin was collected in real time, as the object slid over the first five ridges of the skin, that is, along 50 mm of skin. Fast Fourier Transformation (FFT) was applied to this force signal to extract the signal frequency. The slip speed information v was determined as a ratio $v = f/D$ between the frequency of the force signal, f, and the inter-ridge distance, D, of the artificial ridged skin according to [45]. A virtual window corresponding to the slip speed guidance was vertically displayed on the left side of the screen, and its size was 300x700 (width x height) pixels. The slip speed was linearly mapped to the speed of a rectangle dropping vertically on the screen and notifying about the slip occurrence and slip speed of the object. The size of the virtual object that slips was 50x50 pixels. Given the computed slip speed and the length of the object on the skin surface of the robot hand, a time limit within which the user had to react in order to stop the slip before the object leaves the surface of the robot hand was computed. Given the size of the experimental object, the upper bound of the time interval within which the user should react to slip was $t_{Rmax} = 120/v$ seconds, assuming that the speed remained constant. The range of the real object's speed was converted to a speed range of 21 to 104 pixels/s for the virtual object to fit the graphical window, because our focus was on the users perception of relative speed.

4.2.2. *Grip force guidance*

The grip force was graphically displayed as a horizontal expansion or contraction of a solid bar. A virtual window of 500x200 pixels was displayed on the right side of the screen. Based on *a priori* information about the range of joystick displacement and the range of robot fingers flexion around the experimental object that were previously computed offline in the calibration phase, a proportional mapping between the joystick displacement and the length of the graphical bar was computed. According to Eq. 2 and the measured grip force calibration values, the grip force (in Newtons) can be derived as a function of the joystick displacement J_x: $F_f = 9.76 \cdot 10^{-4} \cdot J_x - 20.64$. The size of the virtual object was 1x50 pixels initially and 245x50 pixels upon full expansion. This object expanded by 0.3 times the value of the joystick displacement, representing the grip force. When both slip speed and grip force guidance was provided to the user, the two corresponding graphical windows were active as described in Sections 4.2.1 and 4.2.2. In general, the graphical interface design took into account geometrical representations and arrangements of the virtual objects to provide an unbiased user response [46]. The virtual objects had similar sizes, while graphics representing changes in slip speed or increased force intensity occurred at reasonable rates. Furthermore, for sessions in which one stimulus was present, the corresponding graphical window was shown central to the screen.

4.2.3. *Performance feedback*

At the end of each session, the performance in stopping slip in time and adjusting the grip force within the safe margins against slip were displayed to the user. This feedback appeared in a graphical window sized 300x450 pixels on the lower right side of the screen. The reaction time to slip was relayed to users as a binary performance result. We compared the users' reaction time to slip with the maximum computed time until the object falls from the robot hand, t_{Rmax}. Thus, apart from the value of their reaction time to slip, the users were presented with the messages "Efficient reaction time", which was associated with a green-colored square, and "Object fell" associated with a red-colored square, for successful and failed reaction time, respectively.

The performance result related to grip force took one of three values. If the user's grip force F_f resided within the safe margins against slip, i.e., $T_g \leq F_f \leq T_g + 1.8$ N, then participants were presented with the message "Efficient grip force", the joystick displacement value, and a graphical green-colored square. Overshooting the stable grip force interval, i.e., $F_f > T_g + 1.8$ N, presented participants with the message "Object was crushed", the displacement value of the joystick and a red-colored square. Lastly, when the joystick displacement was lower than that corresponding to the efficient grip force, i.e., $F_f < T_g$, participants were alerted about slip by being presented with the displacement value of the joystick, the message "Object is slipping" and an orange-color square.

Participants were provided with short training prior to experiments. It consisted of two sessions for each type of experiment, in which they could experience with random slip speeds and a virtual weight whose joystick displacement corresponding to the defined onset of slip, T_g, was 350 units and represented a hypothetical mass. The order of the three test experiments across all participants varied in order to cross-balance the study. One session spanned from 5 to 20 seconds, depending on the speed of the object. The pause between sessions was about 5 seconds, which coincided with the time taken by the experiment assistant to relocate the object to the initial position with a controlled movement of the motor. There was also a pause between experiments of about one minute. In total, the three experiments collectively took a maximum of 30 minutes.

5. Results

In this section, we analyze the performance of the users in stabilizing their grip depending on the type of guidance with which they were fed back, and depending on the accuracy of provided slip information.

5.1. *Response time to slip*

The user reaction time to slip was determined depending on the type of guidance provided to the user, and on the values of the object's speed, as shown in Fig. 5. Although the actually programmed speed (at the level of the microcontroller) of the object was in the set of $\{10, 30, 50\}$ mm/s, computed speeds varied in the set of $\{10, 20, 30, 40, 50\}$ mm/s. This variation will be analyzed in a following section. The red stars in the figure represent the upper bound of the time interval within which the user should react to slip, t_{Rmax}, and are specific to the experimental object. A reaction time to slip larger than this value implies that the participant was not sufficiently fast to stop the slip of the object while it was on the robot hand.

Figure 5A shows the reaction time with respect to computed slip speed of the object when participants were relayed with object's slip speed guidance alone. The Pearson correlation coefficient, computed between the slip speed of the displayed object and the reaction time to slip, was -0.40, suggesting that there is a medium negative correlation between the two variables. A Kruskal-Wallis test was run on the data, which yielded $H(4) = 29.85$. The p-value, estimated by Chi-Square with four degrees of freedom, is $p = 10^{-5}$, indicating that there is a significant difference between response times depending on the speed of the object.

Similarly, Fig. 5B presents the reaction time corresponding to experiments with grip force guidance alone. The Pearson correlation coefficient was -0.09, indicating that there is no correlation between the speed of the displayed slipping object and the participants' reaction time to slip. The Kruskal-Wallis non-parametric analysis-of-variance test was used to determine significance between the reaction times across computed slip speeds. The test yielded $H(4) = 12$, and $p < 0.01$ by Chi-Square.

Figure 5C shows the reaction time with respect to computed slip speed of the object when slip speed and force guidance were both provided to participants. According to the Pearson correlation coefficient, -0.26, there is a reduced negative correlation between the response time to slip and the moving speed of the graphical object. In this case, the Kruskal-Wallis test for the response time to slip across computed speeds yielded $H(4) = 10.64$ and $p < 0.05$.

In addition to these tests, we also investigated whether the reaction time limit, specific to each slip speed, affects the user response time to slip. Thus, the normalized distance between the maximum time duration required for the object to slip away from the robot hand, t_{Rmax}, and the time response of the user was computed. It yielded 208.5 in the case of grip force guidance alone, 82.5 in the case of slip speed guidance alone and 150.5 with force and slip speed guidance combined.

The overall results of these tests indicate that users' response time to slip is well distributed within the amount of time they are given to stop slip most notably when slip feedback is present. As such, when the slip speed is low, their response time is slower, whereas if the slip speed is high, their response time is faster. This tendency is most prominent when slip speed guidance alone was fed back to participants. For this reason, significant differences in time response across slip speeds are not expected, though they can be present.

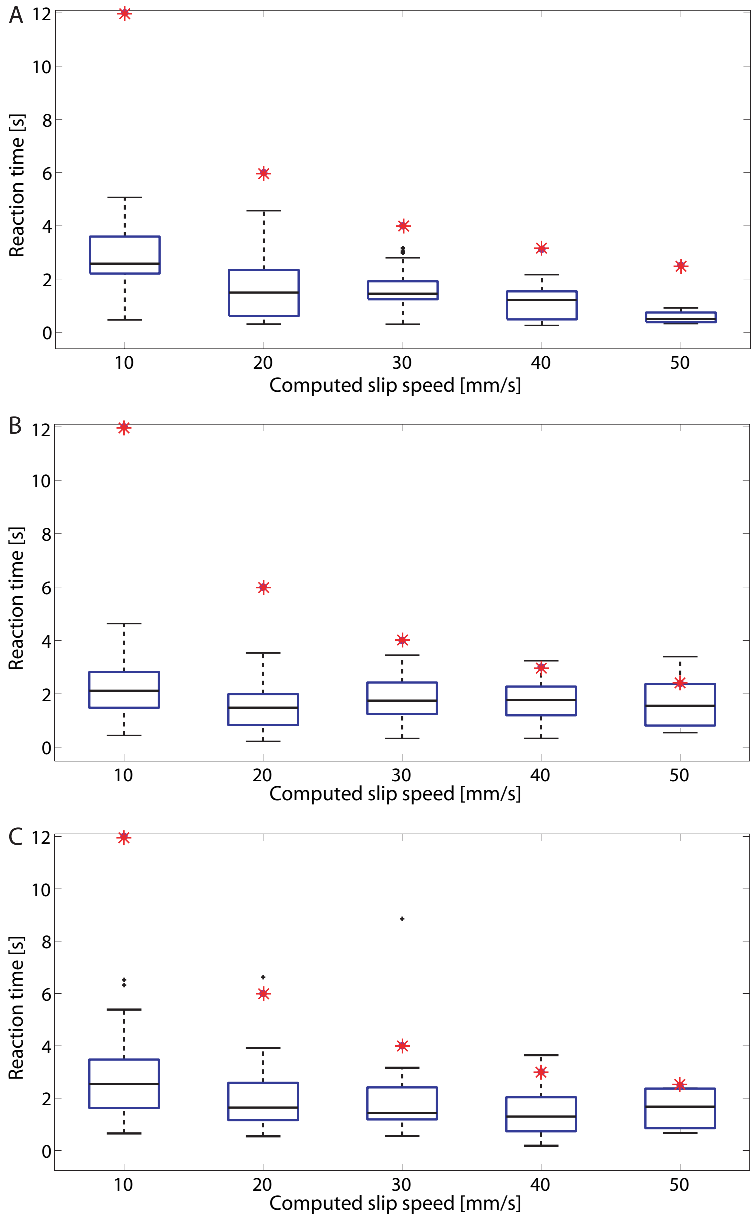

Figure 5. Reaction time with respect to computed slip speed with slip speed guidance alone (A), grip force guidance alone (B), and both guidances combined (C). The red stars represent the upper bound of the time interval within which the user should react to slip and are specific to the experimental object.

5.2. *Grip force response*

Given that two weights that require different grip forces to maintain them within the slip margins were used, we investigated whether users were able to accordingly adjust their grip force and reach stable grasp as defined in the calibration process. Figure 6A shows the grip force response with respect to the two expected grip forces characterizing the slip margins for the two different weights, when participants were provided with grip force guidance only. The horizontal dashed lines delineate the grip force interval within slip margins as defined in the calibration process. Noticeably, with this type of guidance, the grip force responses from the participants were mostly condensed within the stable grip force region. The non-parametric Kruskal-Wallis test was applied to the actual grip responses across the expected ones, yielding $H(1) = 16.18$ and $p < 10^{-3}$. When participants were informed about both their grip force and the object's speed, the grip force responses corresponding

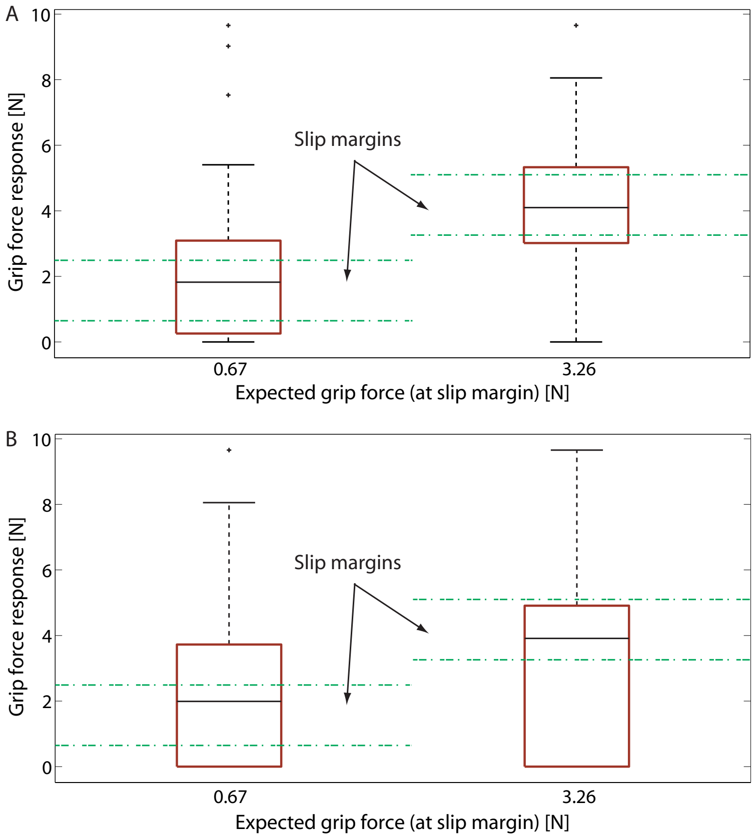

Figure 6. Grip force response with respect to the grip force at slip margin corresponding to two weights, with force feedback guidance alone (A) and with slip speed and force guidance combined (B). Slip margin designates the grip force interval below which the object starts to slip. This interval was determined empirically using the robot hand platform.

to the two weights were distributed as in Fig. 6B. The same non-parametric Kruskal-Wallis test for this case yielded $H(1) = 3.92$ and $p < 0.05$. The plots clearly show that the users can easily adjust the grip force to reach a stable region of the grip, if grip force information indicative of the slip margins is available to them. Having such information, users of a prosthetic hand could maintain a minimal force on a manipulated object.

5.3. *Slip speed variance*

A significant factor in the design of haptic interfaces and artificial skins of prosthetic hands for stable grasp is the user's sensitivity to the slip speed detected by the artificial skin [14] [17]. Consequently, we investigated the influence of the variance in the tactile sensor output on the grasp performance. We analyzed the variance of the slipping object's speed, as computed, compared to the motor's speed driving the object via the cable (Fig. 7A) and, furthermore, the influence of the speed variance on the user performance (Fig. 7B). The percentage of similarity between the programmed motor speed and computed speeds is presented in the confusion matrix in Fig. 7A, where light grey stands for high similarity and dark grey denotes low similarity. The matrix reveals speed variations of about 10 mm/s for expected speeds below 30 mm/s. Largest variations were recorded at motor speeds of 50 mm/s. There exists a trend according to which computed speeds are lower than the programmed motor speeds. Although the real velocity of the object during actual slip was not track, this has been done in another independent study of our group. Under similar conditions, slip was recorded using a camera. It was thus found that at the beginning of the slip, the real velocity of the object was lower than the expected one, due to the initiation of motion [40]. For

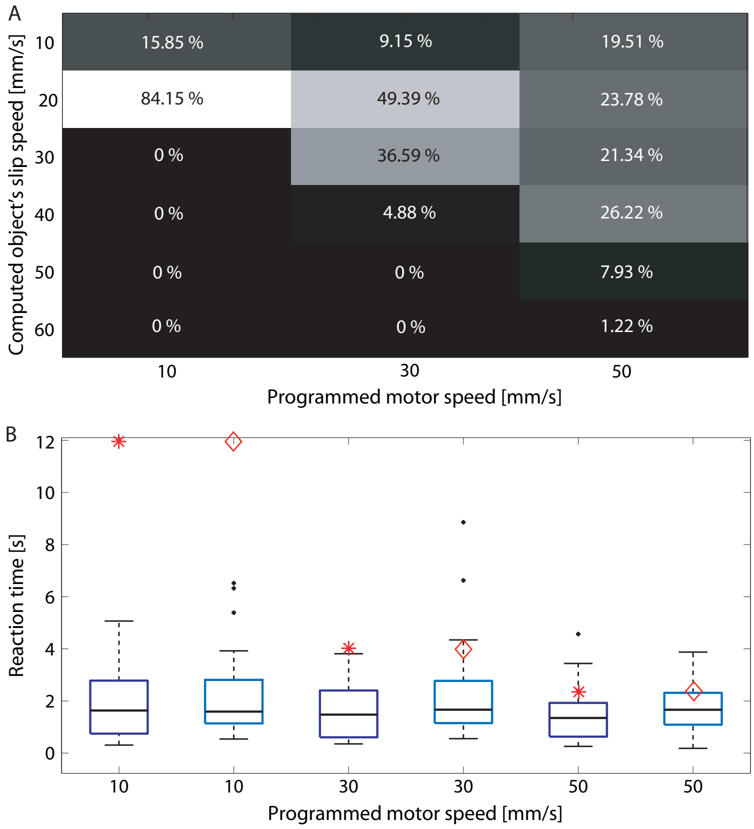

Figure 7. Slip speed variance. (A) Computed object's slip speed with respect to the programmed speed of the motor driving the cable-attached object. (B) Reaction time with respect to expected slip speed, with slip speed guidance alone (bars with stars), and with slip speed and force guidance (bars with diamonds).

this reason, we surmise that speed variations towards values lower than expected may be due to the same reason. As expected, the dynamics of the object slipping on the ridged surface diversifies the slip speed compared to the programmed motor speed. Nonetheless, it is not the scope of this study to validate the performance of the slip speed detection which was carried out in [40], but to analyze the reaction of the users with respect to the computed slip speed.

We further investigated whether the variance in the detected slip speed would significantly affect user performance in grasp stability in the robot hand setup. As such, Fig. 7B illustrates the user reaction time to slip associated with the motor speed in the two experiments in which information about the computed object's speed was available to participants. The results show that even for maximum slip speeds such as programmed motor speeds lower than 30 mm/s, the users manages to stop the slip. This is because the user's reaction time in this case is within the duration of the object's slip on the surface of the robot hand. The result suggests that variations in slip speed does not significantly affect the performance of overcoming slip.

6. Discussion

6.1. *Experimental procedure*

In the present study we investigated relations between grasp stimuli and user response that could suggest stable grasp control schemes for hand prostheses, in particular for our group's platform. We found that user reaction time can be modulated by information about the slipping object's speed and that the user's grip force can be adjusted using information about the grip force at slip

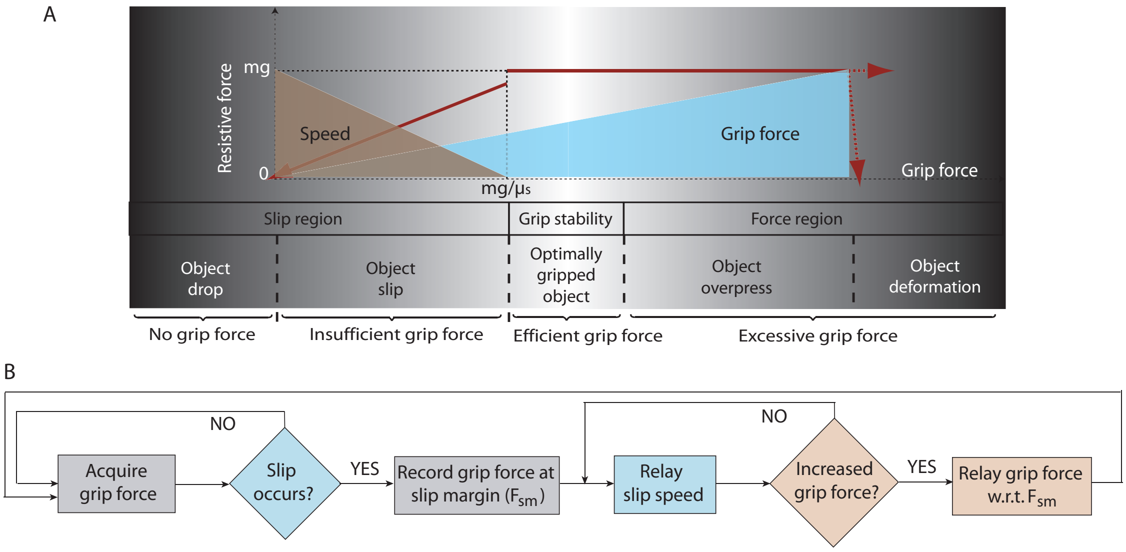

Figure 8. Grasp stability chart. A. Chart of the grasp. B Proposed haptic methodology for user-driven grasp stability.

margins. Quantitative tuning of these grasp control mappings need to be further addressed, taking into account more complex scenarios of the grasp process. For example, experiments in this study did not consider parameters such as object size, initial position on the hand or geometry. While the former two parameters may affect the results of the user's reaction time, the latter one may affect the slip speed detection. Experiments also did not include a user-actuated prosthetic hand, which was not necessary for testing our hypothesis. A continuous physical interplay between the user's grip force associated with the positions of the prosthetic hand's fingers and the object speed would make more difficult the evaluation of the isolated role of slip speed and grip force at slip margin in grasp stability. Thus, the prosthetic hand was used as a passive sliding platform to provide a more realistic experimental procedure due to its size constraints relative to the size of the tactile sensor and that of the held object involved in the slip. Although a completely virtual environment would have been sufficient to test the role of these two variables for grasp control, we used a minimal physical setup, e.g., an object sliding on the robotic hand's palm equipped with a tactile sensor, such that (1) we assess the effect of the slip speed computational variance on the user's grasp control and (2) we advance our groups hand prosthesis system closer to full integration.

The FSR sensor was only used to extract the force frequency in order to detect object slip speed. The sensor was not used to acquire the grip force because it exhibited hysteresis. Due to this reason, grip force was encoded by joystick displacement. The accuracy in detecting slip speed with the artificial ridged skin decreased as the slip speed increased. While for slip speeds of 10 and 30 mm/s the detection performance was reasonable. However, the slip speed of 50 mm/s had the largest variance. Processing the force signal to extract the slip speed required a series of frequency computations across ridges of the artificial skin in order to provide an averaged value for the slip speed. Due to a high slip speed and a consequent short distance traveled by the object on the artificial skin, there were less frequencies to average in order to ensure a more accurate computation of the slip speed. However, from our numerous experimental observations, 50 mm/s is a significantly high slip speed, which is unlikely to often occur during grasping. The computed speeds were discretized in five values (10, 20, 30, 40, 50 mm/s) to allow controlled classes of users time responses to slip, across which we could run statistical analysis.

6.2. *Perspectives of haptic design*

The results show that best adjustments of response times to slip are obtained through slip speed guidance alone, and that an optimal grip force is achieved with the provision of guidance about grip force at slip margins alone. The fact that the combination of the two types of guidance did not result in best responses for time to stop slip or grip force may suggest that slip and grip force are perceived in a mutually exclusive manner, and providing them at the same time is distracting and inefficient. This inference is intuitive, as slip and excessive force are antagonistic phenomena. Furthermore, this simplification, according to which only one stimulus should be relayed at one time, points out to an easier search for an equivalent haptic feedback.

In an endeavor toward an integrated stable grasp schema, we inquired about user performance related to both overcoming slip and exerting minimal force. We computed the percentage of trials from the second half of the experiments (when a learning trend occurred), in which the grip force exceeded the safe margins, with provided guidance about the object's slip speed, and about slip speed and grip force. The percentages of trials characterized by exceeding grip force with slip speed guidance were 51%, 24%, 30%, 34% and 27% at speeds 10, 20, 30, 40 and 50 mm/s, respectively. When provided with slip speed and grip force guidance, participants failed to maintain the grip force within the safe margins in 10%, 18%, 30%, 36% and 41% of trials for speeds 10, 20, 30, 40 and 50 mm/s, respectively. According to this analysis, it appears that if the user acquires information about the grip force corresponding to the slip margin through learning, the probability of applying an excess of grip force to overcome slip is diminished.

A rough map of the grasp process is represented in Fig. 8A. The map shows the interplay between the slipping object's speed and the user's grip force. It also illustrates that a potential method to reach stable grasp is indicated by the gradients that result from the quantitative information about slip speed and grip force. Consequently, a possible grasp control scheme based on the results of this study is presented in Fig. 8B. Given an unstably grasped object, if slip is detected, the prosthesis user is relayed slip occurrence and speed information during the slip. The grip force at the moment when slip occurrence feedback is relayed to the user is an indication of the grip force at slip margin, about which the user can become vigilant. Given the slip stimuli, the user is expected to increase the grip force [12]. If slip no longer occurs, then the user will be provided with grip force guidance. In this way, the prosthesis user could find the appropriate grip force to exert on the object, with respect to the grip force at the slip margin, and eventually stabilize grasp. Quantitatively, the availability of slip speed information may assist the user in avoiding a potential impulsiveness to exert an excessive force on the object while overcoming slip, while the availability of mass-dependent grip force at slip margin may help the user adjusting the grip force with more precision for an optimal grasp configuration. This proposed control scheme for stable grasp is fundamentally intended for the acquisition and updating of grasp-related sensorimotor coordinations by the prosthetic system's wearer in the initial phase of grasp practice, when the interface between the user and the prosthetic hand is highly prone to perturbations.

7. Conclusions and Future Research

The current study investigated means and proposed a strategy to control stable grasp. Based on a user-centered approach to grasping with prosthetic hands, we found that stable grasp mainly depends on the user's time reaction to slip and grip force. Psychophysical experiments with human participants, in a combined real and virtual environment, show that reaction time to slip can be modulated by relaying object's speed, while grip force can be adjusted with information about the grip force at slip margins. This study also provides an integrative view upon grasp by connecting the feedback interface with tactile sensors available in our group. The artificial ridged skin tested in this study is a promising tactile sensor for extracting information related to slippage. A main focus for future work is testing our proposed stable grasp strategy in a fully integrated and functional prosthetic system encompassing a user-operated robot hand equipped with the artificial ridged skin, and a corresponding haptic device [17].

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