Developing new frontiers in the Rubber Hand Illusion: Design of an open source robotic hand to better understand prosthetics

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Abstract—In psychology the Rubber Hand Illusion (RHI) is an experiment where participants get the feeling that a fake hand is becoming their own. Recently, new testing methods using an action based paradigm have induced stronger RHI. However, these experiments are facing limitations because they are difficult to implement and lack of rigorous experimental conditions. This paper proposes a low-cost open source robotic hand which is easy to manufacture and removes these limitations. This device reproduces fingers movement of the participants in real time. A glove containing sensors is worn by the participant and records fingers flexion. Then a microcontroller drives hobby servo-motors on the robotic hand to reproduce the corresponding fingers position. A connection between the robotic device and a computer can be established, enabling the experimenters to tune precisely the desired parameters using Matlab. Since this is the first time a robotic hand is developed for the RHI, a validation study has been conducted. This study confirms previous results found in the literature. This study also illustrates the fact that the robotic hand can be used to conduct innovative experiments in the RHI field. Understanding such RHI is important because it can provide guidelines for prosthetic design.

I. INTRODUCTION

A well-known paradigm in psychology is the Rubber Hand Illusion (RHI) where people have the illusion that a fake hand is becoming their own [1]. This illusion is created by placing a fake hand next to the hand of the participant, previously hidden by the experimenter. Both real and fake hands are repetitively touched with a paintbrush. The subjects feel the brush on their hand but only see the brush moving synchronically on the fake hand. Doing so, they start to feel that the fake hand is becoming their own. There are different measures to quantify the efficiency of this illusion: for example the proprioceptive drift, questionnaires and physiological measures. The proprioceptive drifts consists in measuring the difference between the spatial drift perceived before and after the RHI induction. Questionnaires quantify participants subjective feelings of the robotic hand being part of their body (ownership) and controlled (agency) by themselves [1]. Physiological measures quantify change (e.g. skin conductance or heartbeat frequency) when threatening stimuli are applied to the fake hand.

Authors have suggested that visual mismatch between the two hands [2], or asynchronous simulation [3] removes the illusion. Experience of asynchronous movements between fake and real hand can help to better design prosthetics, as they can explain how patients feel it. Indeed, Ehrsson et al. [4] have shown that amputees are also experiencing the RHI: they feel that a fake hand is becoming their own hand even if they have lost their natural hand. Moreover the RHI is also valid by using advanced prosthesis available on the market [5]. Such experiment has important clinical implications as it can help to better understand how amputees can assimilate their prosthesis as a real part of their bodies [6], [7], [8].

These past years, the development of robotic prostheses has emerged with hand [9], arm [10], [11], transfibial [12], [13] and transfemoral [14], [15] prosthesis. Consequently, research on prosthesis integration in the field of the RHI is not limited to hand but can also concern other parts of the body like legs [6], [16]. Prosthesis improvements must not only target the mechanical aspects but also integrate its psychological perception by the person.

Recently, many authors have proposed to evaluate RHI using an action based paradigm [17], [18], [19]. In this situation, movements of the real hand are imitated by the fake hand. For example, the index finger of the fake hand is physically connected with a wood stick to the index of the participant [17]. These action based paradigms are of real interest as they produce more stable RHI [20]. However, the classic action based RHI experiment lack of realistic motion replication between real and fake hands or is unable to control precisely the conditions of the experiment. This paper explains the design of a low-cost robotic hand that can mimic finger movements of the participants, increasing realism and efficiency of the RHI experiment. The purpose is to remove the current limitations of available research methods on the RHI. Many robotic devices have been used to experiment the RHI [2], [21], but it is the first time that a robotic hand is proposed for the active RHI paradigm and experimentally validated. Beckerle et al. [6] are developing a similar robotic device to test the Rubber Leg Illusion (RLI) [16], [20].

The programming of this new robotic hand has been conceived to allow the modification of the experiment parameters, such as introducing a delay between real and fake hand motions or selecting finger motions. Such device could also easily establish incongruent conditions, like for example the movement of a finger of the real hand resulting in a movement of another finger of the robotic hand. These new experimentation possibilities push the boundaries in the RHI
research field.

Next section describes in further details the idea of developing such robotic hand where functional specifications are deduced from the existing literature but targeting a low-cost and easy to build device. Section III focuses on the design and realization of the hand, putting the emphasis on how these costs and manufacturing aspects have been integrated. Due to the innovative aspect of such experimental device, its validation is explained in section IV. Finally section V examines possible usage scenarios and limitations of the robotic hand.

II. PSYCHOLOGICAL REQUIREMENTS

For the past decades, plenty of robotic hands have been developed and used for different tasks [22]. However, the main interest remains grasping and manipulation where force exerted by the fingers can be quite important. Due to the limited physical size and to the high level of performance required for dexterity and strength, such devices are very complex mechatronics and are also very costly. These high prices restrict large testing groups. Moreover, it is very difficult for non-specialists to use or program these robotic hands. They are also not appropriate for psychological testing because it is not necessary to grasp anything in the RHI experiment while a high speed is required to avoid delays. None of the different hands design existing, both as research prototype [23] or commercial [24], are adapted for the RHI.

While most robotic hands are dimensioned on force/torque, this hand should be designed for speed. The robotic hand provided should be affordable and sufficiently reliable. As the device is mainly intended to psychologists it should be easy to use and to control. One of the main problems that psychologist are facing conducting a research is the experimenter bias [25]. This bias is due to the influence experimenter can have on subjects (even unconsciously), so they provide the response he wants. To avoid situation where the experimenter is in contact with the participant while running the experiment, everything should be done through a remote computer. This is why a criterion to increase the RHI experiment objectivity is to control it via a computer.

In order to overcome actual limitations of the rubber hand experiment, the aim is to create a strong illusion. Therefore an important aspect is that the robotic hand looks and has the dimensions of a real hand. Appearance seems to be an important criterion: performing a vague resemblance will increase the hand eeriness [26] and in consequence, tends to wear off the illusion [27]. Because the robotic hand is meant to create an illusion with many different participants hands, it should have a general form and dimension.

One of the major motivations for this improved version of the rubber hand is that it should be possible to mismatch human and robotic fingers. For example, if the participant moves his thumb, the little finger will move on the rubber hand. It should also be possible to introduce a delay between participant and fake hand movements as it has already been done manually in [3].

Moreover, the robotic hand should be very precise in time. It means that, when required, the robotic hand should move exactly at the same time than the participant’s hand. An oversized delay between the two movements kills the illusion [3]. We have to ensure that the delay between real and fake hand does not exceed a maximum value. According to Christ et al. [16] different maximum delays can be found in the literature, varying from 70ms up to 230ms. Furthermore, fingers should also move at the same speed. In consequence, this robotic hand should minimize reaction delays and increasing actuation speed compare to usual low-cost robotic hand [28]. As the hand of the participant remains hidden, the movements of the robotic hand do not need to be precise. If the position of one finger of the robotic hand is few degrees below the position of the corresponding participant finger, he will not perceive it [2]. Because the participant only looks at the fake hand, he has only an approximate idea of his fingers’ bending. Fingers position between real and fake hand can then differ. Finally, the robotic hand should be sufficiently compliant to avoid hurting volunteers or experimenters [29]. A correspondence between psychological requirements and specifications for designing the robotic hand is summarized in table I.

III. DESIGN

A. Mechanic

The robotic hand has been released under a non-commercial Share Alike [30] licence. It means that this project has been made open hardware and open software, allowing everybody to copy the device for non commercial purposes and to perform their own experiments with it. Authors believe that it is the most effective way to spread

<table>
<thead>
<tr>
<th>Psychological requirements</th>
<th>Design specifications</th>
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<tbody>
<tr>
<td>Affordable device</td>
<td>Low cost materials and manufacture</td>
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<td>Similar look than a real hand</td>
<td>Realistic fingers movement</td>
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<td>Possible to introduce delays</td>
<td>No physical connections</td>
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<td>Minimum delay</td>
<td>High speed actuation</td>
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<td>Real hand covered</td>
<td>Reduced motion precision</td>
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<td>Avoid experimenter bias</td>
<td>Computerized control</td>
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<td>Safe to use</td>
<td>Compliant actuation</td>
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Fig. 1. Index finger mechanism. Springs are acting as joint while providing necessary return force for extension. The nylon wire (in transparent) is acting as tendon.

TABLE I
CORRESPONDENCE BETWEEN PSYCHOLOGICAL REQUIREMENTS AND DESIGN SPECIFICATIONS

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the robotic hand over a large community. Moreover, this community can actively participate to the project and improve it if they license the modified project under the identical terms. The whole device is based on the Do It Yourself (DIY) principle where the manufacturing and assembling of the device does not require any technical knowledge [31]. Therefore this robotic hand is designed in a way that allows being manufactured with 3D printing. Indeed, 3D printing is now increasing widespread and available in fablabs or online additive manufacturing services. Detailed assembly instructions as well as explanations have been made available on Instructables website: http://www.instructables.com/id/Robotic-hand-for-the-Rubber-Hand-Illusion-RHI/

The device is based on a simple mechanism where each finger is actuated by a hobby servo motor. The hand has a total of five degrees of freedom (dof), one for each finger. Each finger is composed of 3 pieces linked together with springs which act as articulations. There are two low stiffness springs (spring rate of 0.407N/mm) per articulation as can be seen in figure 1. The use of springs also simplifies the mechanism while providing a cheaper hand. Indeed, this simplified mechanism reduces both manufacturing complexity and assembling time: springs are inserted into the finger’s parts and fixed with a bore. This makes the assembly easier because it is only necessary to push the springs in their corresponding holes. No glue, screws or any other type of fixation is needed. Another advantage of the springs is that they can be operated without any risk of injury for the participants. A wire connected to the finger goes through the hand to be pulled by a servo motor. This acts as a tendon to realise the flexion of the finger. To bend the finger completely, the wire has to be pulled by a distance of 3.3cm. By relaxing the wire, extension is executed by the springs. The wires are made of fishline, an easy to buy cheap high strength wire. The wire tendons are connected to a lever arm (of 5cm length) fitted on the servo-motors which convert rotary motion into linear motion. The hobby servo-motors used in the prototype are Tower Pro mg995, available in any hobby store. They provide a torque of 10kg/cm at a speed of 0.16s/60 deg. A complete flexion of one finger corresponds to 90 deg of rotation of the servo-motor. Consequently, a complete flexion-extension can be obtained in a minimum time of 0.48s, in other words, the maximum finger frequency for a complete movement is around 2Hz. These servo-motors are installed in a closed box (see figure 3) used to decrease the noise produced. The wrist contains a 3 passive dof, enabling to orientate the robotic hand in a similar position to the hand of the participant.

One concern of this design is the vibration of the fingers. Indeed, after being pulled, the wires are released and the fingers return to their initial extended positions. Due to the elastic behaviour of the springs, small vibrations appear near the equilibrium position. An implemented solution on the design is to change the equilibrium position, this way the springs are still exerting a force when fingers are extended. Fortunately, this problem disappears when a glove is put on the hand as it provides sufficient damping.

Figure 2 shows the robotic hand made of 3D printed ABS plastic. The use of this material is suitable [32] because the hand is not used for grasping. Its only purpose is visual. Moreover, ABS plastic is much lighter than traditional computer numerically control (CNC) milled parts in metal, decreasing the inertia and consequently increasing the velocity of the fingers. The hand is easily reproducible and the blueprints have been specially adapted for hobby 3D printers such as the RepRap [33]. The project has been made open hardware, thus blueprints are available on https://grabcad.com/library/affordable-3d-printed-robotic-hand-1.

B. Control

A schematic of the control is illustrated on figure 4. Participant are wearing a glove that measures their finger position using flex sensors [34]. As these flex sensors are bended, their resistances increase. Although these low cost sensors are not very accurate, they are appropriate for the
requirements. The resistance variation at each sensor is measured at a sampling frequency of 100Hz. This voltage is then converted into a corresponding target angle, which is sent to the hobby servo-motors. An initialisation procedure ensures that the measured voltage is correctly mapped to the corresponding angle. The participant is asked to open and close completely his hand for calibration. The relation between finger bending and motor rotation is obtained with a linear mapping using the calibration values. Recording the minimum and maximum value of the flex sensors, the glove can be adapted to different sizes of the participants’ hands or experimental conditions. The robotic hand is controlled by an Arduino: an easy to program low cost micro-controller [35]. The Arduino reads the data from the sensor glove, but it can also be controlled with a computer using Matlab. Through serial communication between the Arduino and the Laptop, a Matlab script is able to tune precisely the robotic hand parameters. Because this project aims at being accessible and open source, the Arduino code can also be found on the Instructable dedicated page (see link above).

Experimenters can easily interact with the robotic device using only one Matlab code line. This code can be included in a Matlab experiment routine (e.g. using the PsychoToolbox [36]). There are three Matlab functions that the experimenter can use: `startHand`, `stopHand` and `changeData`. `startHand` enables the movement of the robotic hand. In a same way `stopHand` disables the movement of the robotic hand. These two functions allow to rigorously control the time the hand is working with Matlab. The third function, `changeData`, changes the desired parameters of the hand. First, it can switch the digit correspondence creating a mismatch between the two hands. It can also introduce a precise delay between them. Furthermore it is also possible to impose a movement to the finger with a desired frequency. This third function is interesting because it can be used during the experiment to change the parameters of the hand. There is a constant delay of 500ms between the Matlab command and its application by the device. This is not a problem because Matlab only send the "start", "stop" and "parameter" instructions. The control of the robotic hand is done in real time by the Arduino with a maximum delay of 10ms. This small delay induced by the Arduino does not have an influence on the illusion [16]. In traditional action-based paradigm, changing the experimental conditions requires time and direct intervention of the experimenter [17], while in the case of the robotic hand, a command line is sufficient.

IV. VALIDATION

A validation study [37] is conducted to see if the prototype is able to induce a Robotic Hand Illusion (RobHI). The hand of the participant is placed below the robotic hand as it is shown on figure 5. The efficiency of the RobHI is measured using proprioceptive drift and adapted questionnaires from [1] and [17]. The study consists of three experiments where 42 participants were recruited, all volunteers and randomly assigned to one of the experiments (14 participants per ex-

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All three experiments contain a common baseline condition based on the method of Ehrsson et al. [38] where the robotic hand reproduces index finger movement. These baselines conditions are the active, synchronous and congruent conditions. The three experiments compare respectively active versus passive, synchronous versus asynchronous and congruent versus incongruent conditions.

In the active condition, participants entirely control the robotic hand, whereas in the passive condition, the hand moves by itself, at a frequency of 1Hz. Paired sample t-test on questionnaires scores indicated that agency and ownership diminished significantly in the passive condition compared to the active condition, t(13) = 5.040, p < .001 and t(13) = 2.905, p < .01, which tends to indicate that the proprioceptive drift in the active condition was significantly higher from 0, t(13) = 2.156, p = .05 but not in the passive condition, p > .1, which tends to indicate that the RobHI occurs only when participants actively control the hand.

The second experiment is similar to the first one, but in this case synchronous versus asynchronous conditions are tested. In asynchronous condition, a delay of 0.5 second is
introduced between real and fake hand movements. Paired sample t-tests indicated that agency and ownership scores decreased significantly in the asynchronous condition compared to the synchronous condition, respectively $t(13) = 5.169$, $p < .001$ and $t(13) = 4.494$, $p = .001$. One sample t-tests indicated that the proprioceptive drift in the synchronous condition was not significantly different from 0, $p > .1$, but that the proprioceptive drift in the asynchronous condition was significantly lower than 0, $t(13) = -3.999$, $p = .002$, indicating a repulsion in the asynchronous condition. The results showed that a RobHI is created in the synchronous but not in the asynchronous condition.

The third experiment is specific to the robotic hand. The first condition is similar to the two other experiments: robotic hand is reproducing index finger movements of the participant (congruent condition). In the second condition the movements of the index finger are resulting in the movements of the little finger of the robotic hand (incongruent condition). A paired sample t-test indicated that ownership decreased significantly in the incongruent condition compared to the congruent condition, $t(13) = 3.487$, $p < .005$. Paired sample t-test indicated that agency also diminished significantly in the incongruent condition compared to the congruent condition, $t(13) = 3.167$, $p < .01$, suggesting that even if agency stayed high in the incongruent condition, the reduced sense of ownership could equally influence the sense of agency. One sample t-tests indicated that the proprioceptive drift in the congruent condition was significantly higher than 0, $t(13) = 2.325$, $p < .05$ but not the proprioceptive drift in the incongruent condition, $p > .1$, indicating that participants felt their own hand to be closer to the robotic hand only in the congruent condition.

Consequently, it shows that it is possible to conduct many new experiments on the RHI. At the end, all the baseline conditions show that the participants experience a strong RobHI. A more detailed statistical analysis and discussion of these experimental results can be found in [37]. In this study, only one finger movement was used but future study could of course use the five fingers at the same time.

V. CONCLUSIONS

This paper has proposed an innovative robotic device to extend the frontiers in the RHI experimentation field. Apart from providing insights in psychology, RHI allows also to design better prostheses [39], since not only the mechanical properties are important, but also the acceptance by the user. A list of functional requirements has been established for this new device, a low-cost and an easy to manufacture solution being added as main objectives. Low-cost has been achieved by using 3D printed parts where all hardware and software data has been published open source. The simplicity of the design together with the mounting guidelines allow the assembly by a non-expert. A validation session has shown that the device performs well as RobHI and is inducing a RHI. The robotic hand offers many other advantages and opens the possibility for many research possibilities. It allows not only to produce strict experimental conditions via Matlab, but makes it also possible to modify these conditions at multiple levels without changing the hardware. The current design could be improved in a next version, by adding a motor to actuate the wrist or by avoiding finger bouncing when controlled at high frequencies. More research could be also carried out on the link between the RHI and the Uncanny Valley [26].

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REFERENCES


