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Multi-Actuator Haptic Feedback on the Wrist for Needle Steering Guidance in Brachytherapy

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***Abstract*—Brachytherapy is a cancer treatment procedure where long needles are inserted towards an inner body target in order to deliver radioactive seeds that treat the cancer cells. Controlling the trajectory of the needle is very challenging as it deviates from a straight path during insertion. In this paper, we present the pilot study of usefulness of a wristband with haptic feedback designed to help surgeons guide the needle towards a desired destination. The wristband embeds eight miniature actuators distributed around the wrist. The actuators are controlled to generate different haptic stimuli, each of which informs the user about a necessary needle steering manoeuvre. We describe the design of the wristband and its evaluation in two distinct user studies. In the first study, we evaluate how accurately users can identify the vibration patterns. In the second study, we focus on how the user responds to these patterns while performing needle insertion into tissue in an environment with high cognitive visual load. The reported average success rate in identifying the haptic pattern and the success rate in performing the correct action during needle insertion are 86% and 72%, respectively. These results suggest that the device could work in tandem with a needle steering algorithm to help surgeons achieve high quality implants and develop needle steering skills.**

***Index Terms*—Haptics and haptic interfaces, steerable needles, needle deflection, brachytherapy.**

1. MOTIVATION

Brachytherapy is a very efficacious prostate cancer treatment with excellent success rates of 89-96% in 5 to 12 years of follow-up in single and multi-institutional studies [1]. In this procedure, long needles are inserted into the patient's body in order to deliver tiny radioactive seeds. Once the seeds are delivered, the radiation emitted from them will treat cancer cells over the course of several weeks, while minimizing the radiation exposure in the adjacent healthy tissues.

Despite its excellent success rates, close scrutiny of the technical aspects of brachytherapy indicates considerable room for improvement. Accurate needle steering towards the target is very challenging as the surrounding tissue applies forces to the needle causing it to bend [2], [3], [4], [5]. In turn, the surrounding tissue moves, stretches and deforms. Combined, needle deflection and tissue displacement pose a strong risk for inadvertent target misses. Controlling and compensating for these effects during manual needle insertion is crucial to minimize seed placement error. Typically, on-line assessment of needle targeting accuracy is performed under ultrasound image guidance [6]. To view the ultrasound images, the surgeon must look away from the patient and towards a monitor while manoeuvring the needle. This division of attention complicates the procedure. Due to these challenges, the outcome of brachytherapy relies on surgeons with sufficient expertise and case volume. Studies have shown that inexperienced surgeons or surgeons with low case volumes have a higher risk of performing implants of suboptimal quality [7].

These limitations make current radiation practice limited to treat the entire prostate gland uniformly. It has been demonstrated that local control increases with higher radiation dose [8]. The concept of tumour subvolumes has generated a need for more precise seed placement to target specific areas of dominant tumour within the prostate. Very precise seed placement can allow for focal treatment of dominant intra-prostatic lesions rather than treating the entire prostate.

To improve needle targeting accuracy, needle-tissue modelling and robotic-assisted needle steering have often been the focus of research. Several robotic systems have been proposed to automatically insert a needle and undertake the appropriate corrective actions to control its trajectory towards the target [9]. Despite many advantages offered by robotic needle steering, i.e., high accuracy, repeatability, and reliability, such systems have not yet been widely adopted in clinical practice. Likewise, manual needle steering is generally not implemented by surgeons. An intermediate solution to bring needle steering into operating rooms can be sought in combining needle steering planners that calculate optimal steering manoeuvres with manual needle insertion control, as it has been shown to increase needle targeting accuracy [10]. This may be facilitated if one can guide the surgeon in an intuitive way to effectively insert the needle.

In this paper, we report a pilot study for a wristband designed to transmits relevant information to the surgeon about an implant during brachytherapy via haptic feedback. The wristband embeds several actuators placed around the wrist. As the surgeon inserts the needle, vibrotactile patterns inform the surgeon about necessary steering manoeuvres, that could be calculated by a needle steering algorithm. In this way, information can be transmitted in an intuitive manner

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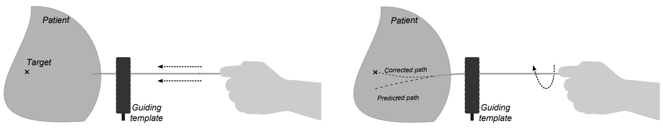
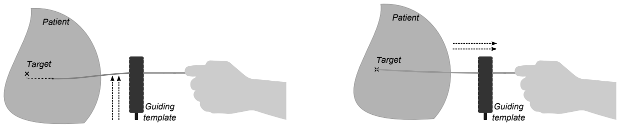


(a) Accelerate or decelerate (b) Needle rotation



(c) Push up or down (d) Target reached

Fig. 1. Needle steering manoeuvres aiming to guide the needle tip towards a clinical target. The arrows indicate the action undertaken by the surgeon: (a) Acceleration and deceleration controls the effects of needle insertion velocity on the deflection, (b) needle rotation about 180° reverses the direction of deflection, (c) forces applied to the needle shaft at the entry point into the patient cause the needle to steer in the opposite direction, and in (d) the needle reached the target and the needle can be withdrawn.

without increasing the visual load in the operating room. In contrast to existing systems where the needle insertion and steering are fully automated, our approach relies on a device that simply offers additional information to the surgeon. This is particularly suitable for providing inexperienced surgeons relevant information to reduce implantation errors.

The paper is structured as follows. In the next section we will review existing wrist-based tactile systems and haptics-aided needle insertion. Before we present the design of the wristband and the associated vibrotactile patterns in Section 4, we present needle steering manoeuvres that can be used in brachytherapy to control the needle deflection (Section 3). Finally, we present an evaluation of the device's ability in conveying information to the user in different scenarios.

2. RELATED WORK

Several studies have highlighted the efficiency of haptic feedback as an alternative to visual feedback for transmitting information when visual attention is needed for other tasks [11], [12]. In conjunction with visual feedback, haptics-assisted training is particularly effective in teaching skills that have a critical kinesthetic element such as surgery [13], with the advantage of producing better long term retention of a learned skill when compared to visual feedback [14].

In the operating room, the use of a tactile wristband is perhaps the least invasive way for transmitting relevant information to the surgeon via haptic stimuli. Numerous tactile systems have been developed for transmitting eye-free information [15], [16], [17], [18]. In [17], a wearable wristband with a single actuator on each wrist was developed to deliver directional information to the user. [19] demonstrated that such tactile feedback can help eyes-free communication with a mobile device, with a reported identification rate of 73%. Systems with multiple actuators have also been developed to increase recognition rates. In [20], a wristband was used to convey information about colliding objects during teleoperation. Results demonstrated that dynamic patterns, i.e., actuators placed at different locations that are alternately turned on and off, have higher recognition rates when compared to static patterns. Similar results were found in [15] where a tactile watch-shaped device was developed to provide pedestrians with navigational directions and information about points of interest. The authors concluded that one-way horizontal and vertical actuation movements presented lower recognition rates than circular or alternating lateral movements of the studied vibrotactile patterns. Another application in spatial guidance presented in [21] reported that users achieved better performance with a vibrotactile feedback when compared to the corresponding verbal instructions.

Haptic feedback has also been used in computer assisted needle insertion. Applications include haptic simulators [22], and teleoperation schemes with force feedback to steer flexible needles in a soft tissue [23], [24], [25], [10]. Instrumented needles can be used to provide in-vivo measurement of needle insertion forces allowing them to be reflected to the surgeon during teleoperation [26]. An example is the system proposed in [27], where a teleoperated system controls a needle driver that simultaneously rotates and translates the needle. In [24], haptic feedback in comparison to no force feedback reduced tissue puncture overshoot by 50%. In [25], a master robot provides kinesthetic-vibratory feedback to the user to help him/her guide the needle towards a target. The study demonstrated that vibratory feedback is more effective than visual feedback in conveying such steering manoeuvres.

These indicate that haptic feedback can convey relevant navigational information with higher effectiveness when compared to visual instructions. In the operating room, it is particularly useful to allow the surgeon to receive eye-free information while focusing attention on the patient and the surgical task. We propose to develop a device to help the surgeon guide needles during the brachytherapy procedure. Our device consists of a multi-actuator wristband that generates intuitive haptic stimuli in order to inform the surgeon about necessary steering manoeuvres. The patterns are configured to be in accordance with the natural gestures required for each action. To the best of the authors' knowledge, such a device for needle insertion guidance has not been proposed in the literature. Before we address the design of the wristband, let us first review in the next section some needle steering manoeuvres that can be used during brachytherapy.

3. NEEDLE STEERING MANOEUVRES

A schematic of a seed implantation procedure during prostate brachytherapy is shown in Fig. 1. Consider that a 200 mm long, 1.27 mm in diameter needle is inserted into the patient's body to a depth of about 150 mm to reach a clinical target where radioactive seeds shall be deposited. In order to help guide the needle towards this target and to minimize needle deflection outside the patient, the needle is inserted through a rigid guiding template placed near the patient (see Fig. 1a). The template consists of rows and columns of holes placed 5 mm apart. The target is generally defined on a straight path from the selected grid template hole at a desired depth in the patient. As said earlier, the needle will deviate from this straight path due to needle-tissue interaction [4]. To ensure the needle reaches the target, several manoeuvres may need to be performed during the insertion process. We have listed below some needle steering manoeuvres that can be used during brachytherapy in order to control the needle trajectory; these manoeuvres may vary between different physicians.

Accelerate/decelerate: Controlling the insertion velocity is essential to minimizing its effects on the needle deflection. Needle deflection has been shown to increase with the insertion velocity [28]. Paradoxically, if the insertion velocity is too low, tissue relaxation may cause the needle to further deviate from a predicted path, as tissue relaxation is not accounted for in most of needle steering algorithms. Thus, keeping the insertion velocity within a specified range is suitable during the insertion.

Needle rotation: This manoeuvre is based on a key observation that when a bevelled-tip needle is inserted into tissue, the imbalance of forces generated at the needle tip causes the needle to bend following a curved path [9], [29]. By properly rotating the needle base, one can reverse the orientation of the force at the needle tip, leading the needle to deflect in the opposite direction. The depth at which the needle is rotated is the main factor in ensuring the tip reaches the target. In Fig. 1b, for instance, if the needle is rotated too early, the needle tip will overshoot the target. If rotated too deep in tissue, the tip will end up beneath the target at the desired insertion depth.

Push up/down: The kinematics of needle-tissue interaction indicate that forces applied to the needle shaft during insertion can be used to increase the deflection of the needle towards the target [30]. During manual insertion, this can be achieved by applying lateral forces to the needle shaft near the needle's entry point (see Fig. 1c). This action can performed when the needle is expected not to reach the target after the surgeons rotates the needle.

Pause: The insertion process must be temporarily stopped. This action may be necessary in robotic assisted needle insertion, for instance, when the needle's trajectory needs to be recalculated in the steering algorithm.

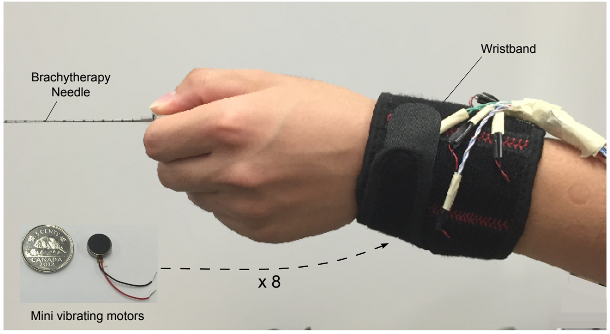
Withdraw: If the actual deviation of the needle from the target cannot be corrected using any steering manoeuvre, the needle must be withdrawn and reinserted.

Maintain: No steering manoeuvre is needed. The insertion can be carried on in the same way until the needle reaches the desired depth.

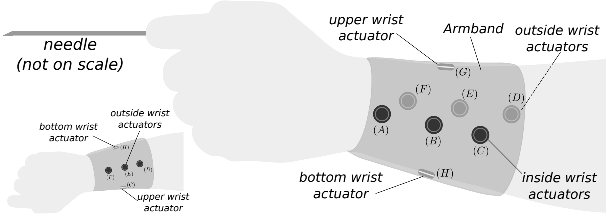
Arrived: The needle tip has successfully reached the target (see Fig. 1d). The seeds can be pushed out of the needle shaft by a stylet for deposition in the tumour and the needle can be withdrawn.

Now that we are acquainted with the steering manoeuvres, let us address the design of a tactile wristband capable of generating haptic patterns to instruct the surgeon about each of these steering actions as he/she inserts the needle.

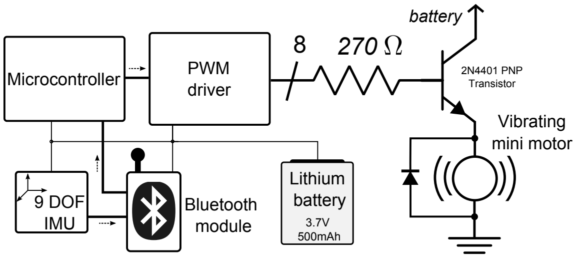
4. THE MULTI-ACTUATOR WRISTBAND FOR NEEDLE STEERING GUIDANCE



(a) Prototype of the haptic wristband



(b) Arrangement of the eight actuators



(c) Electronic architecture of the haptic wristband

Fig. 2. Haptic wristband. In (a) the arm strap and the integrated electronics unit. In (b) the position of the eight actuators. Actuators (A),(B), and (C), are placed on the inside of the forearm, and actuators (D), (E), and (F) are on the outside of the foream. One additional actuator is placed on the top (G) and one at the bottom of the wrist (H). In (c) the electronic circuit. The wristband is controlled by a microntroller and powered by a PWM servo controller. Each of the eight mini vibrating motors oscillate at 150 Hz. The amplitude of the vibration is given by the PWM duty cycle. The position of the wrist is measured by a 9-DOF Inertial Measurement Unit (IMU). The unit communicates with a computer via Bluetooth.

A haptic wristband for needle insertion guidance must convey commands to the surgeon in an easily-identifiable and intuitive way. Misinterpreting these patterns might make the surgeon undertake wrong steering manoeuvres, which may result in inappropriate needle placement. Thus, confusion between the different instructions conveyed via the haptic stimuli must be avoided. Hence, we chose a configuration that allows several actuators to be placed around the wrist such that the user can accurately localize and distinguish the vibrating actuator (see Fig. 2). In fact, localization rates of vibrotactile stimuli have been shown to depend on the distance between the actuators that generate the stimuli. For instance, the average localization rates reported for actuators placed 25 and 50 mm apart are 46% and 66%, respectively [15], [31]. Such rates can increase up to 80% for actuators placed close to arm joints [15], [32]. Experiments have also demonstrated that the higher the area of the skin experiencing the vibrations, the better the perception of the intensity [31]. Thus, we intend to maximize the distance between the actuators and place them as close as possible to the wrist.

A picture of the wristband prototype is presented in Fig. 2(a). The wristband embeds eight mini vibrating motors (1201 mini motor disc from Adafruit, New York, USA) that can be

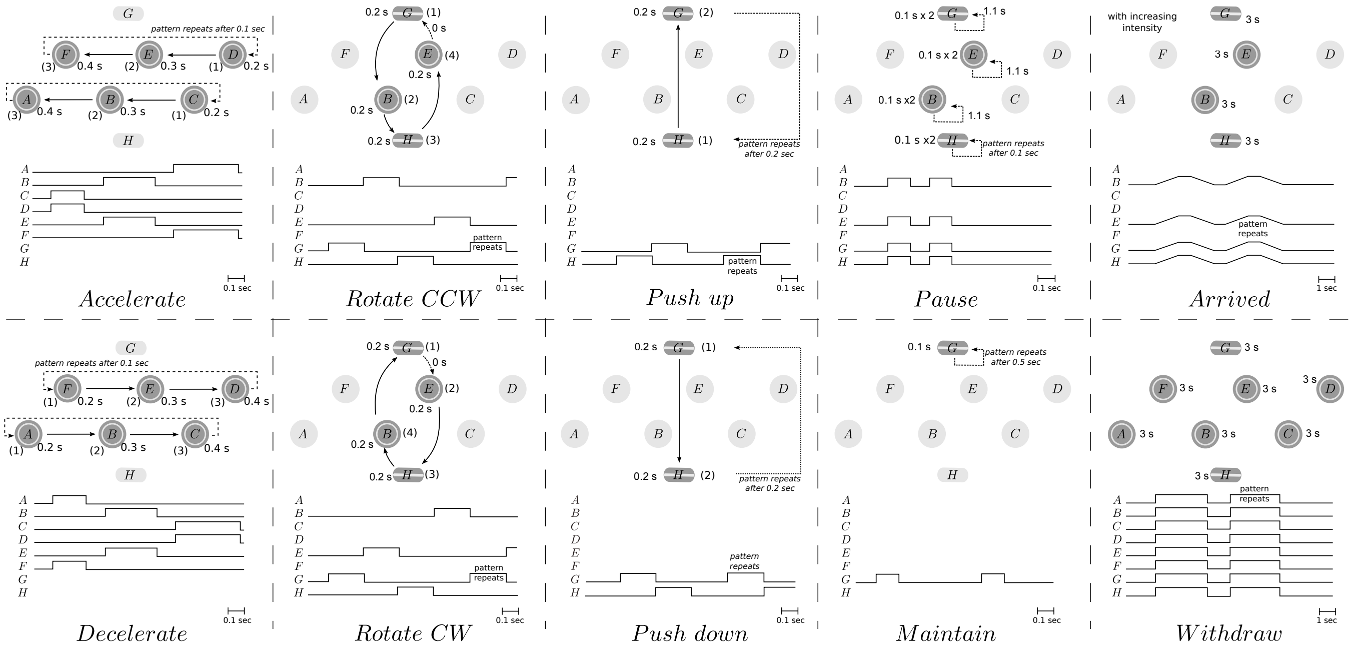


Fig. 3. Haptic patterns representing each needle steering manoeuvre. The number in parenthesis indicates the sequence of activation and the number beside each actuator indicates its activation duration. The plots show the actuators signal as a function of time. Light gray actuators are not used.

controlled independently (see Fig. 2(b)). Each actuator has a diameter of 10 mm and is 3 mm thick. The actuators are placed inside the wristband such that they are always in direct contact with the skin. Three actuators are placed on each side of the wrist and an additional actuator is placed above and under the wrist. The vibration patterns are programmed in a 16 MHz microcontroller (Pro Trinket from Adafruit). The actuators are powered by a PMW servo shield (Adafruit I2C 16-Channel 12-bit) that communicates with the microcontroller via I2C protocol (see Fig. 2(c)). Each actuator vibrates at a fixed frequency of 150 Hz, which is close to its resonance frequency, and the magnitude of vibration is controlled by changing the PWM duty cycle.

The electronics unit also has a 9-DOF inertial measurement unit (Razor IMU from Sparkfun, Niwot, USA - not used in this paper) that measures the displacement and orientation of the arm. A Bluetooth module receives from a computer the information about the tactile pattern that must be displayed, and can send back to the computer the position of the arm wirelessly.

4.1 Vibration Patterns

The layout of the wristband allows the haptic patterns to be implemented in such a way that they reflect the natural motion of the hand during a steering action. The patterns are constructed by changing the vibration duration and amplitude, the pause between the actuator activation and repetition, and the number of activated actuators and their activation sequence. After a preliminary study of different possible patterns, we selected ten different stimuli, one for each of the needle steering manoeuvres described in the previous section. Fig. 3 shows the activation sequence and duration of each actuator and the position on the wrist. The number in parenthesis refers to the sequence of activation. The figure also shows the actuator signals over time.

Each pattern is designed to correspond to a motion metaphor. For *acceleration* or *deceleration*, the outside and inside wrist actuators are activated in the sequence that follows the desired motion of the hand as shown in Fig. 2(a). For *acceleration*, actuators C and D (see Fig. 2(b)) are simultaneously activated for 0.2 second, followed by actuators B and E (0.3 sec) and A and F (0.4 sec). Thus, the sequence of activation is $(CD) \rightarrow (BE) \rightarrow (AF)$ (see Fig. 3). For *deceleration*, the sequence is reversed to $(AF) \rightarrow (BE) \rightarrow (CD)$. The user feels the actuators being activated either forward or backwards. Along the same line, *rotation* is implemented by spinning the actuator activation in the middle row around the wrist in the clockwise (CW) direction (sequence $(G) \rightarrow (E) \rightarrow (H) \rightarrow (B)$) or counterclockwise (CCW) direction (sequence $(G) \rightarrow (B) \rightarrow (H) \rightarrow (E)$). To inform the user about *push up* or *push down* manoeuvres, the actuator on the top of the wrist, followed by the actuator at the bottom and are activated (sequences $(G) \rightarrow (H)$ or $(H) \rightarrow (G)$ respectively), such that the user feels one consecutive tap on the top and then bottom of the wrist.

The remaining patterns implemented in the wristband mostly correspond to warnings and therefore were chosen to be static. *Pause* is represented by two consecutive short vibrations of the middle row actuators ($(GBHE) \rightarrow (GBHE)$) with a repetition interval of 1.1 second, which can be interpreted as a warning signal. For the *withdraw* command, all actuators continuously vibrate for 3 seconds to give the user the impression that something went wrong during the procedure. *Maintain* is represented by a short vibration of 0.1 second of the top actuator (G) that occurs every 0.5 second. Finally, for *arrived*, the central actuators steadily increase intensity to their peak over 1.5 second, and then decrease back to no vibration. This actuation pattern alludes to bouncing against an obstacle.

In the next section we will evaluate the user's ability to identify each of these patterns and see how well they respond to them as they insert a needle in phantom tissue.

5. USER EVALUATION

We carried out two distinct studies to evaluate the suitability of the proposed tactile wristband in conveying information to the user. Due to a steep learning curve in mastering the brachytherapy procedure [7], the objective of the following experiments is not to evaluate how accurately users can perform needle insertion using the feedback provided by the wristband. Such an evaluation is subject to the accuracy of a specific needle steering algorithm that calculates the necessary steering actions based on measurement of the needle position during insertion. Rather, we will evaluate the ability of our device to convey information to the user about each of the steering manoeuvres that can guide the needle towards a target, and how the user responds to a random sequence of those stimuli.

In the first study, we will assess how accurately users can recognize the patterns. In the second experiment, we will reassess the pattern recognition rates while the users are inserting a needle into a tissue as a distraction task.

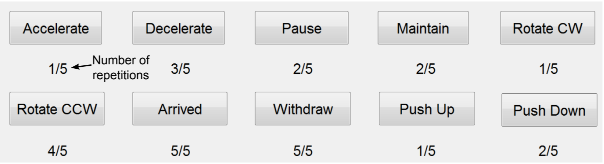
5.1 Study 1 - Identifying the Haptic Patterns

In this experiment we will evaluate the ability of the vibration patterns to correctly indicate the corresponding steering manoeuvre to the user.

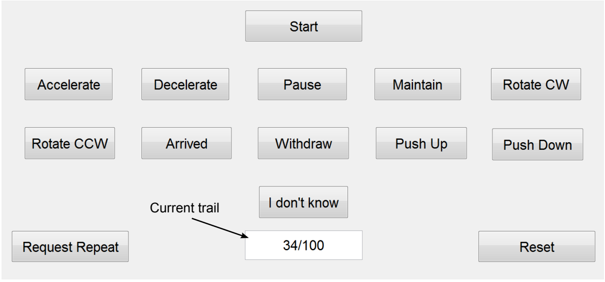
Participants: 10 subjects (7 males and 3 females) with various occupations and ages ranging from 18 to 31 years (average 25 years) volunteered to participate in the experiment. All subjects but one was right-handed.

Procedure: Participants wore the armband on their dominant hand. A computer and a monitor were used to display the experiment's graphical user interface (GUI), and to communicate via Bluetooth with the wristband. The device produced no sound when activated and the vibrating actuators could not be identified visually. Subjects were allowed to get acquainted with the device in a 10 minutes-long training session. During this phase, a verbal description was given for each pattern, explaining the associated meaning and action. Each pattern was then displayed to them five times, in the sequence they chose using the GUI presented in Fig. 4(a). After the learning phase, a random pattern was generated by the wristband and repeated upon request up to two times. Subjects were instructed to identify the pattern by clicking on the corresponding icon in the GUI shown in Fig. 4(b). They could also click on a special icon in case they could not identify the pattern. Each pattern was then presented 10 times to the user in a randomized sequence, totalling 100 trials per user.

Results: The recognition rate and the confusion between the patterns are summarized in Fig. 5. Over 1000 trials, the average recognition rate was 86%. The lowest observed recognition rate was 77%.

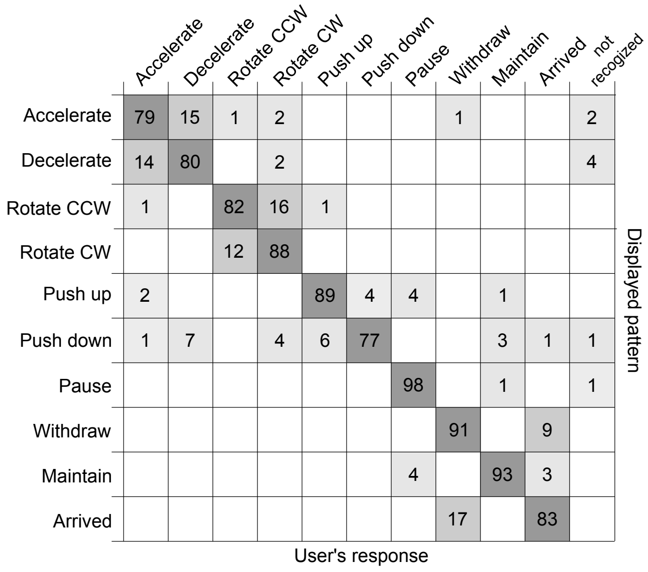


(a) GUI presented to the user during the learning phase



(b) GUI presented to the user during the first experiment

Fig. 4. Graphical user interface (GUI) presented to the user during the training phase (a) and during the first user experiment (b). After a haptic pattern was displayed to the subjects, they were instructed to identify the pattern by clicking on the corresponding icon.



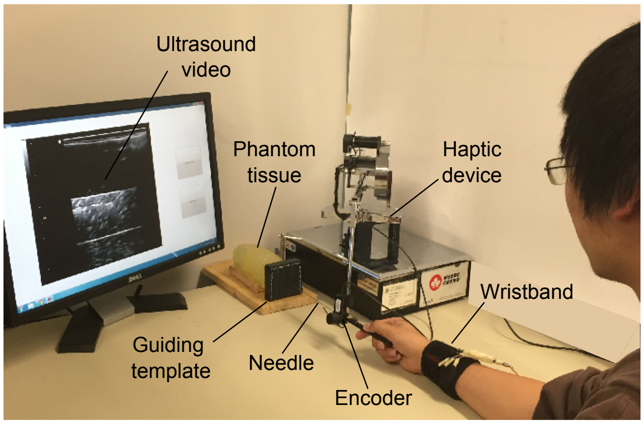
	Accelerate	Decelerate	Rotate CCW	Rotate CW	Push up	Push down	Pause	Withdraw	Maintain	Arrived	not recogized
Accelerate	79	15	1	2				1			2
Decelerate	14	80		2							4
Rotate CCW	1		82	16	1						
Rotate CW			12	88							
Push up	2				89	4	4		1		
Push down	1	7		4	6	77			3	1	1
Pause							98		1		1
Withdraw								91		9	
Maintain							4		93	3	
Arrived								17		83	

Fig. 5. Identification rates and the percentage of confusion with other patterns. Blank cells correspond to 0%. For instance, *Arrived* was successfully recognized in 83% of the trials, and confused with *Withdraw* in 17 % percent of the trials. Over 1000 trials the subjects successfully recognised the patterns 860 times.

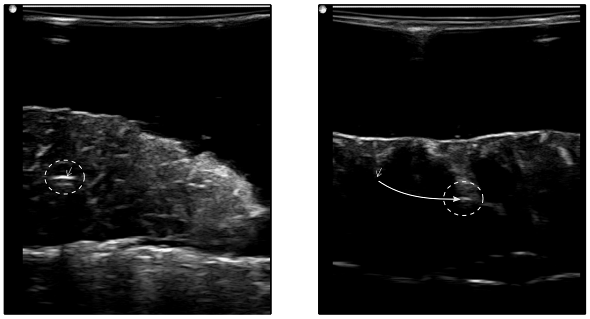
5.2 Study 2 - Responding to the Tactile Stimuli

In this study we will evaluate how users respond to the haptic stimuli while they insert a needle into phantom tissue and track a needle in ultrasound images, similar to the operating room setting. Users were not only required to identify the haptic pattern but also to carry out the manoeuvre they received the instruction for via the wristband.

To this end, a standard brachyhteraphy needle was connected to a Phantom Preminum 1.5A haptic device (from Geomagic, Rock Hill, USA) as shown in Fig. 6(a). The haptic device only tracks the user's gestures and the position of the needle. The needle is inserted into a phantom tissue through a guiding



(a) Experimental setup for needle insertion in phantom tissue



(b) Initial needle location (c) Final needle location

Fig. 6. Experimental setup used in study 2. The needle is connected to a haptic device that measures the user's gestures as the user inserts a brachytherapy needle in the phantom tissue. Ultrasound videos from a needle inserted in biological tissue evolve as the user moves the needle.

template. As the user moves the needle, an ultrasound video of a needle being inserted in biological tissue, acquired previously using the procedure described in [28], is displayed on the monitor. The video plays forward and backwards according to the position and velocity of the needle in order to give to the user the impression of real-time ultrasound image feedback of the needle within the phantom tissue. The ultrasound video shows a cross section of a needle that appears as a bright spot in the image along with other artifacts (see Fig. 6(b)). As the video moves forward or backwards, the position of the needle moves within the images (see Fig. 6(c)). This is only intended to act as a visual cognitive load.

Participants: One month after the first experiment, 7 out of the 10 subjects that had participated in the first experiments (group 1), in addition to a second group of 7 new participants (group 2, 4 males and 3 females), took part in this experiment.

Procedure: All subjects participated in a shortened version of the learning phase used in Study 1, where each pattern was displayed to them 3 times. Following the learning phase, they were requested to hold the needle base and insert it in the phantom tissue. Users wore the wristband on the same arm they used to insert the needle. In a second learning phase, users were instructed on how to perform each of the steering manoeuvres they received the command for via the wristband. Users were allowed to perform each manoeuvre three times. After this learning phase, as the users inserted the needle in the phantom tissue, random commands were transmitted to them by the wristband. The subjects were requested to perform the corresponding action as soon as they recognized the pattern. The pattern was continuously displayed until the action was accomplished. For instance, the *rotation* instruction was given at a random needle insertion depth and kept playing until the user rotated the needle by 180° in the indicated direction. Tasks such as *withdraw, push up/down, rotate* were assumed to be completed when the user moved the needle by -150 mm horizontally, by ± 15 mm vertically, or by ± 180 degrees axially, respectively. During one needle insertion procedure, two to four random instructions were given to each subject, who performed thirty insertions totalling 100 steering manoeuvres per user on average.

During the insertion, the ultrasound video presented to the subjects acts as the source of regular cognitive load during the needle insertion and is intended to keep the user' attention away from the needle. Before the insertion began, the initial position of the needle in the ultrasound images was indicated to the participants. As the participants inserted the needle, they were requested to keep tracking the position of the needle in the images, while performing the requested steering actions. After each insertion, users had to identify the needle position by clicking on the ultrasound image. For each insertion, a different video was used. We recorded the vertical, horizontal and angular positions of the needle along with the time at which instructions were transmitted to the wristband. By analysing the acquired data, we measured the time each participant took to understand and respond to the haptic pattern (reaction time).

Examples of how users responded to a haptic stimuli are shown in Fig. 7. In the plots, a haptic pattern is generated by the wristband at $t = 0$ sec. We measured the reaction time from the time the first repetition of each pattern was completed, until the user moved the needle by a certain amount i.e., 20 mm with increasing velocity for *acceleration*, -20 mm for *withdraw*, ± 15 mm vertically for *push up* or *push down*, respectively, and ± 10 degrees for *rotate*. For *arrived* and *pause*, the time at which the user stops inserting the needle is considered. For deceleration, the response time is measured when the insertion velocity drops by half. If the reaction time was more than 10 seconds the task was considered as incomplete.

Results: Fig. 8 presents the average success rate in performing each steering manoeuvre for each group. Overall, the average found for Group 1 is 85% and for Group 2 60%. Regarding localizing the needle in the ultrasound videos, the success rates for Group 1 and Group 2 are 69% and 57%.

5.3 *Discussion*

Participants of Group 1 took part in both the first and second studies, with similar success rates of 86% and 85% respectively. In the second experiment, the success rate of Group 2, whose members did not participate in the first study, was 60%. If the 10 second cut-off time at which a task was considered incomplete is reduced to 5 seconds, the success rates for Group 1 and 2 are reduced to 72% and 54%, respectively.

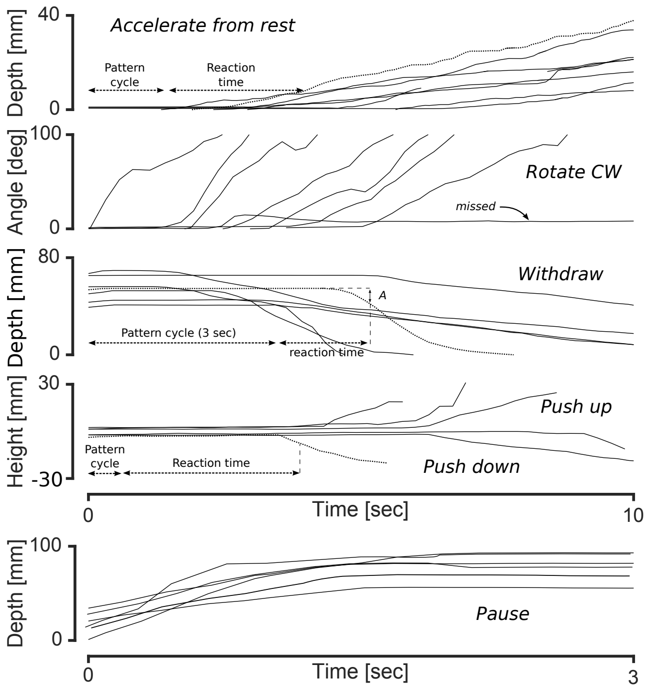


Fig. 7. Examples of user's response to the haptic stimuli. The reaction time starts when one pattern cycle is completed. For *acceleration*, *rotation*, *withdraw*, and *push up/down*, the reaction time stops when the user advances the needle by 20 mm, rotates it by ±10 degrees, retracts it by 20 mm (point A), or move its base vertically by ±15 mm, respectively. For *pause* and *arrived*, reaction time is counted until the insertion stops. Failure in accomplishing the action within 10 seconds is considered as a missed manoeuvre.

Study 2 had a shorter learning phase than Study 1 and presented an important additional cognitive load that was not present in the first study. The obtained results indicate that users can accurately identify and carry out the requested steering manoeuvre conveyed to them via tactile stimuli. The results also showed that Group 1 retained the skills learned in the first experiment, which partially explains the higher success rate when compared to Group 2. Group 2 presented similar confusion between diametric patterns as obtained for group 1 in Study 1.

In both experiments, the lowest recognition rate was observed with the *push down* manoeuvre. Informal feedback obtained from the participants revealed that the actuator placed at the bottom of the wrist could not always be perceived, as it sometimes lost contact with the skin. This issue can be easily corrected by changing the strap used in the wristband. In addition, during the second study, some of this confusion could come from the fact that, if the wrist is rotated during a motion, the upper actuator may no longer be facing up, and the bottom actuator may no longer be facing down. Then any cues given by these actuators would be in the wrong direction in the world frame and may be a source of confusion. We will address this problem in future work by using the embedded IMU in order to measure the orientation of the wrist in real time, and use this information to identify and activate the actual actuators facing up or down.

During the first experiment, the 12% confusion rate between CW rotation and CCW rotation is relatively significant since the motions are opposite. The participants revealed that they were in fact able to successfully identify the direction of the rotation but sometimes got confused with the meaning of CW and CCW when answering the GUI shown in Fig. 4(b). Group 2 also presented a low recognition rate involving the *withdraw* action, which was sometimes confused with *arrived*. However, the obtained results from Group 1 indicate that these recognition rates during needle insertion can be consistently improved when the users receive a longer training session.

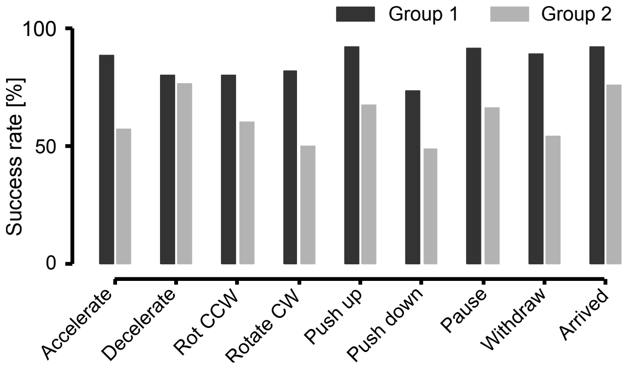


Fig. 8. Success rate in performing each steering action during needle insertion for each group. Each group was composed of 7 subjects. Only Group 1 participated in the first Study. The average recognition rate is 85% and 60% for Group 1 and Group 2, respectively.

Another significant confusion of about 15% was observed between *accelerate* and *decelerate*, which are diametric motions. In both cases, the users received attractive haptic cues, meaning that they were instructed to move in the direction of the vibration. However, evidence indicates that repulsive vibrotactile instructional cues, when the user is instructed to move in the direction opposite to the vibration, can lead to better recognition rates [33]. In order to reduce this error, we will also consider overlapping the activation of the actuators, such that two actuators are briefly turned on at a given time. This can create the sensation of the saltation haptic effect and help improve the illusion of motion generated by these patterns. A user study seeking to create patterns that are uniquely identified can also be carried out. For instance, the use of fundamentally different patterns for vibrating left and right, even if they do not follow the direction of the hand motion, could help reduce the observed errors in future work.

6. CONCLUDING REMARKS

In this paper we present the pilot study for a wristband with tactile feedback designed to transmit information to surgeons during brachytherapy. The wristband has the ability to inform the surgeon about the necessary needle steering actions in real-time, in an eye-free and intuitive manner, such that the surgeon can focus attention on the surgical task. If combined with a needle steering algorithm, the proposed wristband could be used to assist the surgeon to improve seed placement accuracy.

Each steering manoeuvre that can be used to control the needle deflection was associated to a haptic pattern. Reported user evaluation presents an average recognition rate of 86% over 1000 trials. We studied also, in a second experiment, how the user responds to the haptic pattern during needle insertion in phantom tissue while tracking a needle in ultrasound images, mimicking the cognitive load present in the operating room. The success rate in identifying and carrying out the steering manoeuvres was 85% on average for subjects that participated one month earlier in the first study, and 60% for subjects that did not participate in the first experiment. The obtained results suggest that users can accurately perform complex needle steering manoeuvres without knowledge of needle and tissue interaction dynamics.

The system is inexpensive (around $125 CAD) and is easily implementable in the operating room as it does not require any modification in the current brachytherapy practice. In future work, the wristband proposed in this paper will be part of a needle insertion simulator for skills assessment and development in brachytherapy.

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