Chair for Computer
Science 10 (Media
Computing and Human-
Computer Interaction)

RWTH AACHEN
UNIVERSITY

Springlet Apps: Applications of On-Skin Shape Memory Alloy Actuators

Thesis
submitted to the
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Registration date: 08.10.2019
Submission date: 26.02.2020

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Springlet Apps: Applications of On-Skin Shape Memory Alloy Actuators

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Abstract

The importance of *mechano-tactile* actuators lies in their ability to generate natural sensations on the skin such as dragging, pinching and pulling. However, most of the mechano-tactile actuators can be inconvenient to wear as they are heavy and noisy due to hard moving parts in their design. On the other hand, *Springlets* are lightweight mechano-tactile actuators that are easy to build and have a sticker-like form factor. Thus, it becomes important to explore the applications that are possible with a lightweight mechano-tactile actuator like Springlets.

In this thesis, we evaluated a variety of possible applications using Springlets such as weight training, stroke rehabilitation, cutaneous feedback in virtual reality games and haptic navigation. Among these applications, we found that the lightweight design of Springlets suited well with the application area of learning weight exercises. Hence, we chose to explore the area of weight training in detail.

We conducted a user study focusing on an exercise to train the biceps muscle. The study aimed to find if Springlets served as an intuitive haptic guidance interface to learn weight exercises. We studied different placement positions of Springlets to find out the best position to place Springlets on the user's arm while performing the mentioned exercise.

Überblick

Die Bedeutung von *mechanisch-taktiler* Aktuatoren liegt in ihrer Fähigkeit, natürliche Empfindungen auf der Haut wie Ziehen, Kneifen und Ziehen zu erzeugen. Die meisten mechanisch-taktilen Aktuatoren können jedoch unbequem zu tragen sein, da sie aufgrund hart beweglicher Teile in ihrer Konstruktion schwer und laut sind. Auf der anderen Seite sind *Springlets* leichte mechanisch-taktile Aktuatoren, die einfach zu bauen und auf der Haut aufklebbar sind. Deshalb ist es wichtig, die Anwendungen zu untersuchen, die mit einem leichten mechanisch-taktilen Aktuator wie Springlets möglich sind.

In dieser Arbeit haben wir eine Vielzahl möglicher Anwendungen mithilfe von Springlets bewertet, z. B. Krafttraining, Schlaganfallrehabilitation, haptisches Feedback auf der Haut in Virtual-Reality-Spielen und haptische Navigation. Unter diesen Anwendungen fanden wir, dass das leichte Design von Springlets gut zum Anwendungsbereich des Lernens von Gewichtsübungen passt. Daher haben wir uns entschlossen, den Bereich des Krafttrainings im Detail zu erkunden.

Wir haben eine Anwenderstudie durchgeführt, die sich auf eine Übung zum Trainieren des Bizepsmuskels konzentriert. Ziel der Studie war es herauszufinden, ob Springlets als intuitive Schnittstelle und als haptischen Anleitung zum Erlernen von Gewichtsübungen dienen kann. Wir haben verschiedene Platzierungspositionen von Springlets untersucht, um herauszufinden, in welcher Position auf dem Arm des Nutzers Springlets beim platziert am effektivsten platziert werden können.

Acknowledgements

First of all, I am grateful to my parents for their enormous support throughout my studies. I am extremely thankful to my thesis supervisor Anke Brocker for supporting me and putting me on the right track in all stages of my thesis.

I further thank Adrian Wagner for supporting me in the initial stages of my thesis and providing me with the required technical foundation. I thank Krishna Subramanian for advising me on the statistical results of this thesis.

I finally thank all the participants for their time spent in the user study of this thesis.

Conventions

Throughout this thesis we use the following conventions.

Emphasized words are represented in *italics*.

Definitions of technical terms or short excursus are set off in coloured boxes.

EXCURSUS:
Excursus are detailed discussions of a particular point in a book, usually in an appendix, or digressions in a written text.

Definition:
Excursus

The whole thesis is written in American English.

The third person is identified in the male form.

Chapter 1

Introduction

1.1 The Sense of Touch

Touch is capable of transferring physical information

The sense of touch is a natural and also sensitive feeling for most people. This sensation enables us to feel things around us by establishing physical contact with them. It also is capable of transferring information such as texture, the temperature of the material and the pressure that is being exerted from the material.

From the *haptic feedback* that we receive from the physical properties of an object, we can infer a variety of information such as:

Some examples of physical information that can be inferred

1. A signal to initiate an action when the physical state of the object changes.
2. Physical boundaries of the interaction with the object.
3. Inferring the type of object using past experience.

1.2 On-Skin Actuators

Some types of information like physical boundaries of an interaction, pressure, texture are natural to communicate to

Modern actuators are heavy, while shape-memory alloys are lightweight

the user only using the sense of touch as they become very difficult to convey using *non-tactile* techniques. As modern digital devices are often missing natural physical interactions, tactile actuators bridge this gap in enabling natural skin interactions such as dragging, pinching, and pressing. However, most of the modern tactile actuators are often difficult to wear and carry due to the heavy mechanical parts that they employ. Shape-memory alloys (SMA) on the other hand are light-weight actuators that can be fabricated into an on-skin actuator [Hamdan et al., 2019] thereby supporting a light and noise-free operation.

1.3 Applications of On-Skin Shape Memory Alloy Actuators

1.3.1 Motivation

It is important to understand the capabilities of the SMA actuator

As SMA-based tactile actuators differ from heavy-weight tactile actuators in their operation, it becomes important to understand the possible applications that can emerge out of them. The thesis aims to find new ways of interaction with various applications and also aims to find limitations of the SMA-based tactile actuator.

1.3.2 Applications

Stroke Rehabilitation

This thesis explores a cost-effective solution for rehabilitation

A number of people around the world suffer a stroke each year. However, many of them fail to afford robotic rehabilitation devices. This thesis explores the usage of SMA-based tactile actuators as a cost-effective solution for Stroke Rehabilitation by stimulating movement receptors using skin contraction.

Haptic Feedback in Virtual Reality Games

Gaming in a Virtual Reality (VR) environment is visually immersive but lacks the sense of touch when interacting with virtual objects. The thesis aims to explore the usage of SMA-based tactile actuators to simulate natural skin sensations such as a pinch on the skin during a VR game sequence.

This thesis aims to stimulate natural skin sensations during a VR game

Haptic Navigation

Navigation systems have become an integral part of our lives when traveling to new locations. However, Navigation systems are mostly visual systems and are hence not eyes-free which can be distracting during driving. This thesis explores a new method for eyes-free navigation using skin contraction near the wrist.

This thesis explores an eyes-free navigation method

Weight Training Guide

Weight training is a highly adopted method among people to stay fit. However, weight training is highly effective only when the exercise is done in the correct manner. Often, newbies miss details such as timing, pattern, and boundaries of the exercise movement. This thesis explores methods to tackle this problem by using SMA-based tactile actuators to provide haptic feedback in guiding the timing, pattern, and boundaries of an exercise movement.

This thesis explores explores a haptic-feedback method to guide exercise movements

1.4 Outline of the Thesis

This chapter is followed by “2. Related Work” which describes the existing research in the applications introduced in this chapter. In the third chapter “3. Evaluation of application areas”, we describe the applications in detail and evaluate them to finally choose the ’Weight Training Guide’ application to study in detail as we find that it is highly compatible with SMA-based tactile actuators. In the fourth chapter "4. Implementation of Springlets as an Exercise Guide", we describe the design decisions and implementation of the Weight Training Guide in detail. This is followed by "5. User Study" where we evaluate our implementation by performing a user study and applying statistical methods. Finally, the last chapter "6. Summary and Future work" proposes the possible improvements of the designed system.

Chapter 2

Related Work

Research on application areas such as stroke rehabilitation, virtual reality, haptic navigation, and weight training has been going on for decades as suggested by Jack et al. [2001], Ertan et al. [1998], and Chang et al. [2007]. In this chapter, we look at a few approaches that are in the direction of tactile actuators or give a strong foundation towards tactile actuators.

2.1 Stroke Rehabilitation

Occupational therapy is vital but expensive

Occupational therapy can play a very important role in the lives of stroke patients [Steultjens et al., 2003]. This therapy requires skilled therapists to plan necessary activities for stroke survivors in order to improve their quality of life. However, Norman et al. [2014] pointed out that occupational therapy is expensive and highly dependent on the presence of a skilled therapist.

Exoskeleton robotic hand is used to train stroke patients

As a solution, there has been a lot of research in developing robotic devices that assist and train stroke patients in making body movements [Norman et al., 2014]. Ho et al. [2011] proposed one such exoskeleton robot aimed at training a stroke affected hand as shown in Figure 2.1. This device was driven by surface electromyography (EMG) signals that are read through surface EMG electrodes placed on the impaired arm. This ensured that the device assists patients in opening or closing their impaired hand only when they intend to do so.

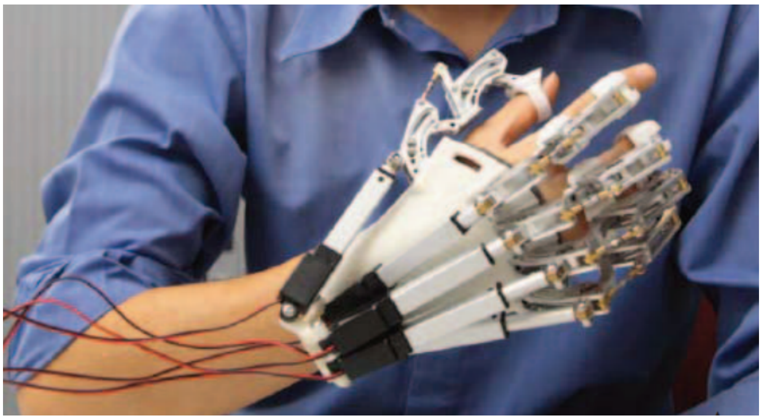


Figure 2.1: Exoskeleton robotic hand training device described by Ho et al. [2011]

Tactile cueing can be an alternative to exoskeleton devices

Norman et al. [2014] suggested that such exoskeleton robotic devices have proven to be beneficial in restoring motor skills in stroke patients. However, they also argued upon the fact that stroke patients can be deprived of such apparatus due to cost and size constraints. They took a step back from traditional robotic devices that use force to guide body movements and proposed a low-cost tactile cueing technique to guide arm movements as shown in Figure 2.2.

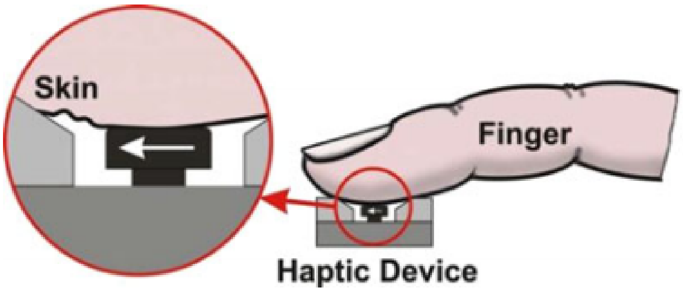


Figure 2.2: Skin stretch on the fingertip as a directional guide [Norman et al., 2014]

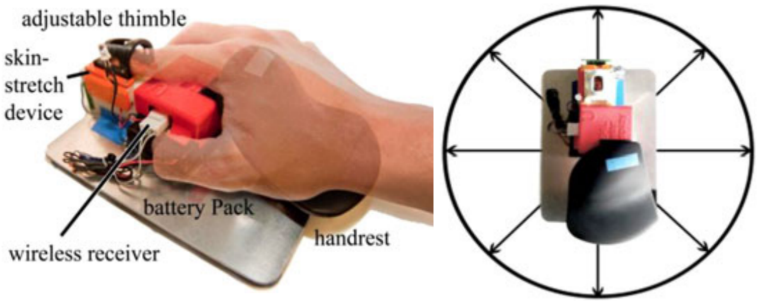


Figure 2.3: Skin-stretch direction guidance device (Left). The eight supported tactile cueing directions (Right) [Norman et al., 2014]

The proposed device (Figure 2.3) looked similar to a computer mouse and could guide the arm on a horizontal plane in eight directions using skin-stretch feedback on the fingertip. User studies concluded that the device was effective in guiding users through random paths within the supported angle limits of the device [Norman et al., 2014]. This suggests that even though the device was not built for helping stroke patients with force feedback, it could leverage tactile cues on the fingertip to train stroke patients in practising certain horizontal motions supporting their speedy recovery.

Skin-stretch is capable of guiding the arm on a horizontal plane

2.2 Haptic Feedback in Virtual Reality Games

Haptic feedback becomes an important aspect of virtual reality environments during natural interactions such as touching, holding or dragging virtual objects [Schorr and Okamura, 2017]. Aiming to make virtual reality an *immersive* experience, many researchers proposed vibrotactile feedback as a haptic feedback mechanism when interacting with virtual objects.

Haptic feedback makes Virtual Reality immersive

In the context of Augmented Reality, Buchmann et al. [2004] proposed a haptic glove fitted with buzzers on the fingertips. Vibrations from the buzzers were programmed to be

Gloves deliver haptic feedback on fingertips using vibration

activated while performing dragging, pressing or holding a virtual object. These vibrations were a placeholder for the actual haptic feedback that one receives while interacting with real-world objects. However, Schorr and Okamura [2017] argued that even though vibrotactile haptic feedback could instantly notify surface touch events and also convey surface roughness information, it was inherently incapable of directly conveying properties such as friction and weight when holding a virtual object.

Haptic feedback on fingertips using skin-stretch is more immersive than vibration

As a solution, Schorr and Okamura [2017] introduced a fingertip skin stretch device (Figure 2.4) that supported movement in three degrees of freedom in Virtual Reality environments. Properties such as friction and mass were conveyed by dragging the device's fingerpad against the skin and stiffness was conveyed by pressing on the skin. Studies indicated that users could recognize changes in mass, friction, and stiffness while interacting with various virtual objects. Moreover, the studies interestingly indicated a strong connection between stiffness and mass as many users perceived changes in stiffness as a change in the mass of the object.

Skin-stretch gives a sense of an elongated arm in VR Games

In the context of Virtual Reality gaming, immersiveness of the experience highly depends on how naturally the haptics are rendered on the body [Yamashita et al., 2018]. Yamashita et al. [2018] described the necessity of a skin stretch technique on the forearm in situations where one needs to extend arms to a superficial limit in fictional games to reach a distant object. They proposed a device to achieve such a skin stretch as shown in Figure 2.5. The device employed motors, a pulley and a sliding rail weighing 200 grams to achieve skin-stretching between the wrist and the elbow. During an arm stretch, it was necessary to increase the weight of the wrist to create a natural experience of an extended arm. This was achieved by the sliding rail by shifting the weight from the elbow towards the wrist during an arm stretch sequence. The device was exhibited at IVRC2017 and the comments from visitors indicated that the users could realistically feel the arm extension [Yamashita et al., 2018].

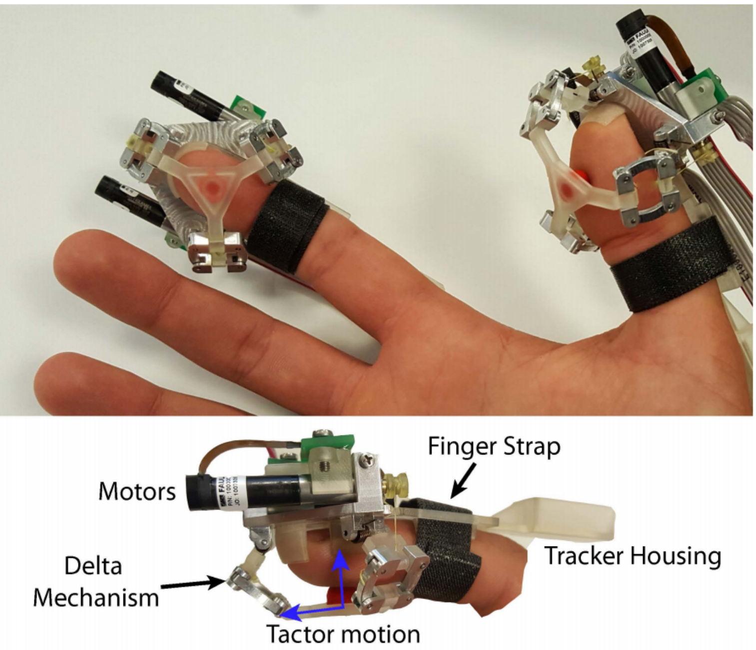


Figure 2.4: Skin-stretch device to convey weight, friction and stiffness information while manipulating virtual objects [Schorr and Okamura, 2017]

Figure 2.5: Skin stretch to deliver superficial hand extension in Virtual Reality games [Yamashita et al., 2018]

2.3 Haptic Navigation

The idea of a Haptic Navigation system goes back to 1998 where Ertan et al. [1998] described a wearable navigation

Haptic Navigation supports eyes-free interaction

system based on vibrotactile feedback. Various research works have explored the placement possibilities of the tactors on various body locations including waist, back and wrists [Dobbelstein et al., 2016] [Ertan et al., 1998]. The motivation for a Haptic Navigation system among researchers was either to guide blind users [Ertan et al., 1998] or to support eyes-free navigation [Pielot et al., 2012].

Vibrating belt functions as a navigational guide

Steltenpohl and Bouwer [2013] proposed one such device to convey a general sense of direction to cyclists using vibrotactors placed in a circular manner (Figure 2.6). The belt was designed to hint the distance of the approaching turn using different vibration rhythms. A variation of pulsed rhythms indicated the distance of approaching turn and the hint to make a turn was delivered using a long and continuous rhythm.

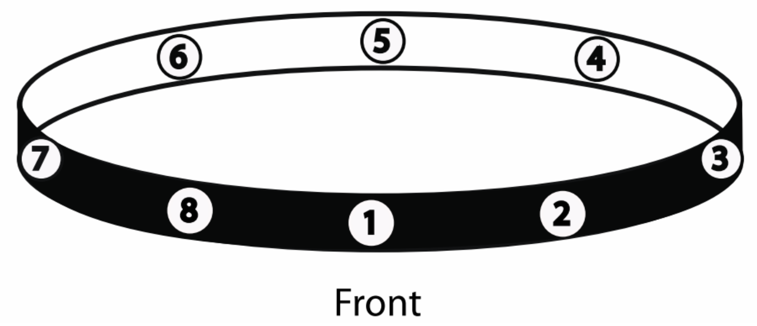


Figure 2.6: Waist-belt for Navigation with numbers showing the positions of vibration units [Steltenpohl and Bouwer, 2013]

Vibrating wristband functions as a navigational guide

Dobbelstein et al. [2016] argued that with the advent of smartwatches, the wrist area was a better area to place the navigational tactors. Similar to the idea of Steltenpohl and Bouwer [2013], they proposed a vibrotactile navigation system to give pedestrians a general sense of the direction instead of turn-by-turn navigation. The device had a form-factor similar to a wristband (Figure 2.7) and the tactors were placed on four areas of the wrist.

Studies from both the research works (Steltenpohl and Bouwer [2013], Dobbelstein et al. [2016]) proved the effectiveness of Haptic Navigation as all the users could reach the destination using the tactile feedback.

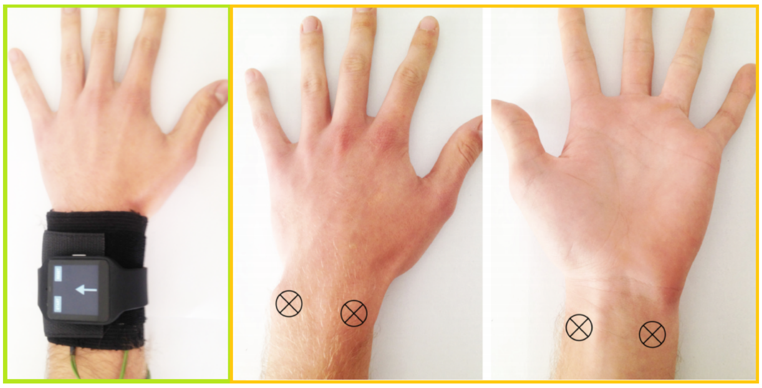


Figure 2.7: Wristband fitted with navigational tactors for Pedestrian Navigation (Left). Position of the navigational tactors (Right). [Dobbelstein et al., 2016]

2.4 Weight Training Guide

Weight training is quite common but involves risk of injury

Numerous people around the world incorporate Weight Training in their routine to maintain fitness [Toor et al., 2017]. However, performing weight exercises in an inappropriate manner often involves the risk of injury [Toor et al., 2017]. This motivated researchers to look for new ideas in the direction of guiding exercise movements and the following sections discusses some of these ideas.

2.4.1 JARVIS : A Virtual Reality Exercise Coach

Virtual Reality can be used to guide exercise movements

Rabbi et al. [2018] introduced the concept of a Virtual Reality trainer to guide weight-exercise movements. The main motivation behind this device (Figure 2.8) was to give feedback to beginners regarding the ideal body movements and speed of the exercise. The device made use of an animated virtual character that performed the exercise sequences to guide the users visually. The device could also identify the type of exercise, provide feedback regarding the exercise and track the progress of the exercise.

Exercise: Sitted Abs
Rep: 0
Duration: 0 sec
Quality: 0%

Figure 2.8: JARVIS : A Virtual Reality Weight Training Coach [Rabbi et al., 2018]

VR trainer is effective and enjoyable

User studies showed that the right set of muscles were better activated during an exercise with Virtual Reality when compared to the traditional approach of naturally performing the exercise movements without VR [Rabbi et al., 2018]. The comments from the users showed that they were motivated to follow the virtual character in doing the exercise and enjoyed the interactive exercise coaching experience.

2.4.2 Haptic Guidance as an Exercise Guide

Skin-stretch near the index finger is known to trigger finger movements

As discussed previously in the Stroke Rehabilitation section, Norman et al. [2014] demonstrated that haptic skin-stretch devices are effective in guiding arm movements (Figure 2.3). Before this work, there was already substantial research in the context of Neurophysiology to prove that sensory receptors on the skin can trigger finger movements [Collins et al., 2005]. Collins et al. [2005] extended the existing research work to investigate if skin-stretch near index finger, elbow and knee joints trigger movements in the respective joints.

Collins et al. [2005]'s experimental setup made use of an elastic band that was connected to the skin through a thread

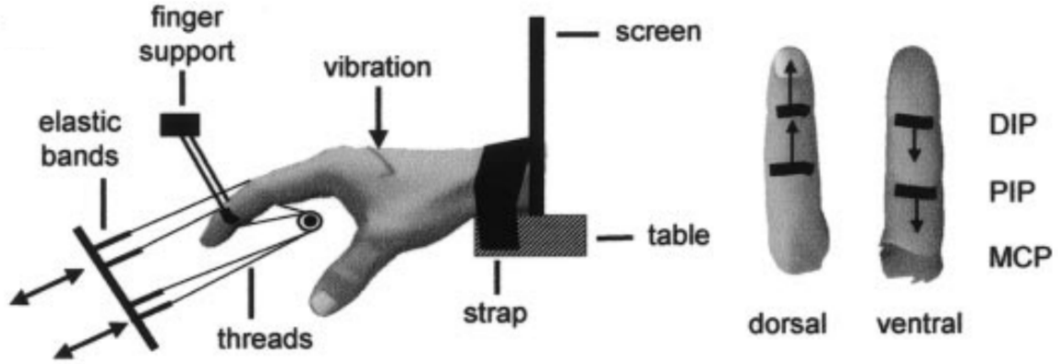


Figure 2.9: Setup to achieve skin-stretch near the index finger joints (Left). Position of MCP and PIP joints of the index finger (Right) [Collins et al., 2005]

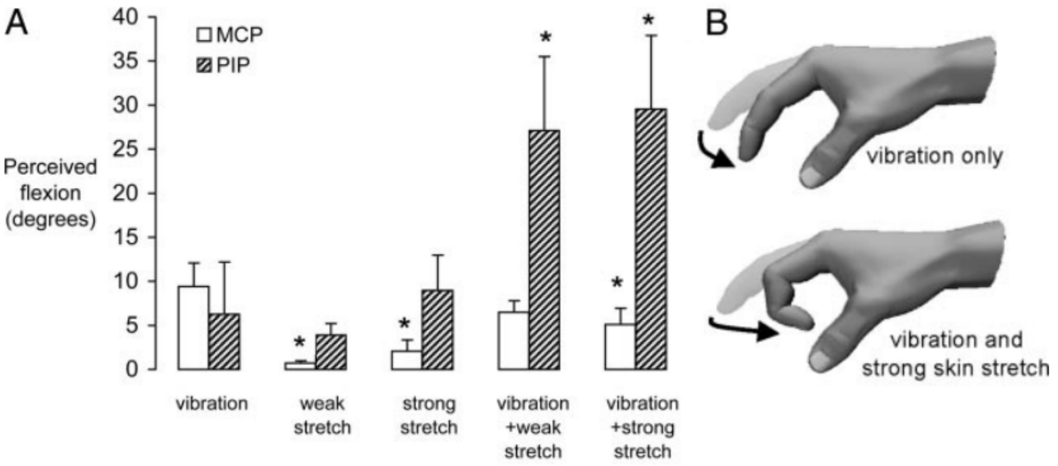


Figure 2.10: **A**: Comparison of mean intensities of finger bending movements in various settings for a group of participants (n=8). **B**: Average perceived finger movements with and without skin-stretch from one participant [Collins et al., 2005]

and an adhesive tape pasted onto the skin (Figure 2.9). Skin-stretch was achieved by pulling and releasing the elastic band alternatively. A study was conducted with 8 participants which aimed at comparing the extent of triggered finger movements with two levels of skin-stretch intensities including and excluding vibration at the MCP and PIP finger joints (Figure 2.9). The results indicated that skin-stretch with vibration near the finger joint triggered a higher bending movement of the finger than with just vibration near the finger joint (Figure 2.10).

The experimental setup corresponding to the index finger

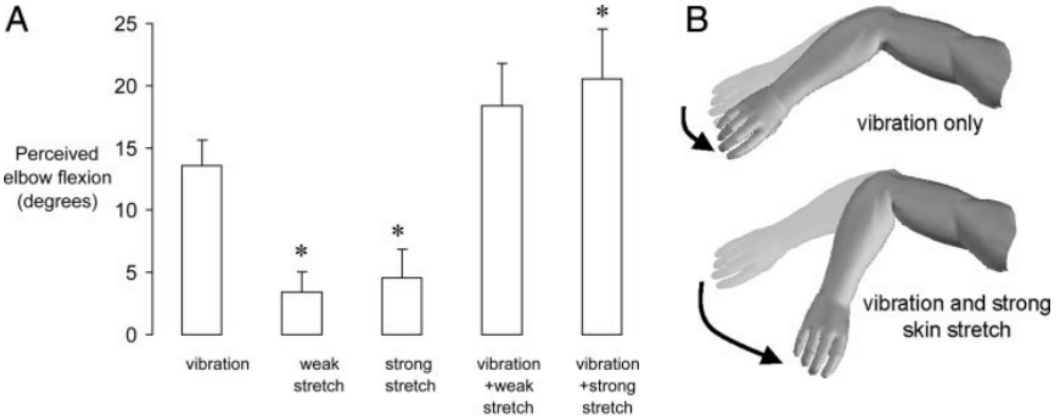


Figure 2.11: **A**: Comparison of mean intensities of elbow bending movements in various settings for a group of participants (n=10). **B**: Average perceived elbow movements with and without skin-stretch from one participant [Collins et al., 2005]

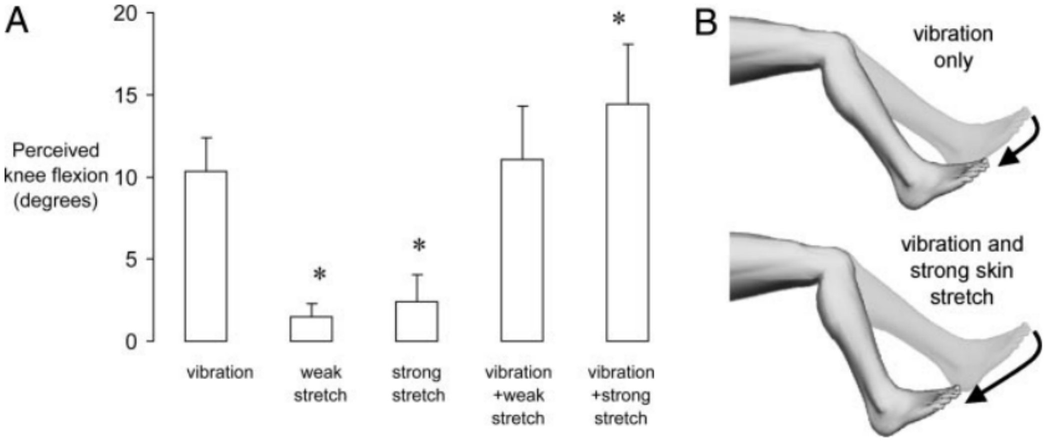


Figure 2.12: **A**: Comparison of mean intensities of knee bending movements in various settings for a group of participants (n=10). **B**: Average perceived knee movements with and without skin-stretch from one participant [Collins et al., 2005]

Skin-stretch is vital in triggering movements

A similar setup was used to compare the extent of triggered elbow and knee movements resulting from skin-stretch near the elbow and knee joints respectively. The results (Figure 2.11 and 2.12) were closely similar to index finger movement triggers indicating that skin-stretch played a key role in triggering movements near the joints.

2.4.3 A Comparison of Various Guidance Techniques

A comparison of Visual and Haptic Guidance

Research work described in the previous sections shows that it is possible to guide body movements using visual and haptic methods. Hence, it is important to understand how both of these methods compare with each other. Feygin et al. [2002] performed a study to compare Haptic Guidance and Visual Guidance techniques where users had to redraw complex trajectories that were learned by only visual guidance, only haptic guidance, and a combination of visual and haptic guidance. To receive haptic guidance, the user held the actuator while the actuator guided the user through the pattern. The redrawing phase was tested using only Haptic guidance and also a combination of Haptic and Visual guidance. The user studies indicated that the timing of the movements was better learned from Haptic guidance when compared to Visual guidance. However, Visual guidance was more effective than Haptic guidance in communicating the pattern of the movement. While in this study, haptic guidance was received by holding the actuator, there also exist other guidance methods such as vibration and skin-stretch.

Visual Guidance is better to learn the pattern while Haptic Guidance is better to learn the timing of the movement

A comparison of vibrotactile and skin-stretch guidance

Bark et al. [2008] compared vibrotactile and skin-stretch guidance methods by setting up a study where the subjects had to move the cursor to a target position from the start position. Subjects started at a random start position and were instructed to move a fixed number of steps to left or right to reach the target position. They had to accurately stop at the target cursor location by perceiving the amplitude of the vibration where the lowest vibration amplitude signified the leftmost end and the highest vibration amplitude signified the rightmost end. Skin-stretch, on the other hand, was delivered using rotational skin-stretch where anti-clockwise stretch signified moving to the left and clockwise stretch signified moving to the right. The user studies indicated that skin-stretch was more effective than vibration in guiding users to the target position. Bark et al. [2008] noted that this was because skin-stretch had the natural ability to convey position information and hence was more intuitive to the user.

Skin-stretch is effective in communicating the direction of the movement

This concludes that Haptic Guidance has several advantages in guiding body movements especially when the timing, direction, and extent of the movement are important.

2.5 Springlets: A Light-Weight Tactile Actuator

Springlets are an alternative to complex mechanical actuators

As an alternative to complex and heavy mechano-tactile actuators, Hamdan et al. [2019] introduced the idea of a light-weight tactile actuator called Springlets. The main driving part of Springlets was the shape-memory alloy (SMA). Spring-shaped SMAs possess the capability of heating and contracting when current passes through it and restoring its original shape and cooling down when the current flow stops. Springlets made use of spring-shaped shape-memory alloys to achieve various sensations on the skin such as pinching, dragging and pulling. Different sensations were achieved by employing an appropriate design while building the Springlet. User studies indicated Springlets could flexibly fit in various parts of the body such as arm, neck, and shoulder generating smooth, noiseless and noticeable sensations. Moreover, it was also found out that the variant designed to generate pinching sensations could be perceived faster (M=1.22 sec, SD=.87) than other variants.

2.6 Contributions of this Thesis

Using springlets as a light-weight alternative for the mentioned applications

While the existing research work targets various application areas such as Stroke Rehabilitation, Virtual Reality games, Haptic Navigation and Weight Training using complex mechanical actuators or vibration units, this thesis employs Springlets as a light-weight, easy-to-build, noiseless tactile interface that can serve as an alternative to complex mechano-tactile actuators employed in various domains. Especially, the area of learning exercises using Haptic Guidance is unexplored and hence this thesis investigates this area in detail with a user study making use of a

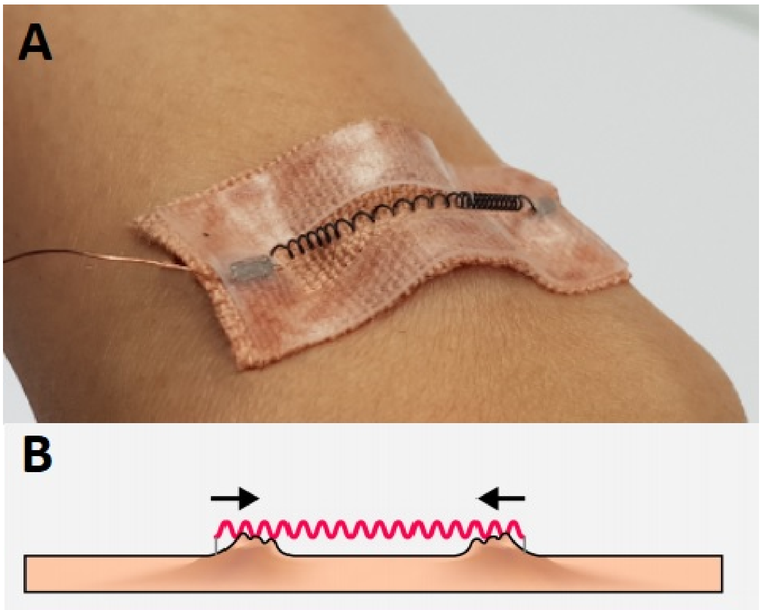


Figure 2.13: **A** : A variant of Springlets that produces a pinching sensation on the skin. **B**: The effect of the Springlet on the skin that turns into a pinching sensation. [Hamdan et al., 2019]

Learning exercises using Springlets is explored in detail with a user study

skin-contraction technique unlike a skin-stretch technique in other studies. While Collins et al. [2005]'s study focuses on creating an illusion of body movements, this thesis focuses on generating noticeable cues that signifies the body movements during an exercise. This thesis also investigates the effectiveness of Springlets in harnessing the power of skin contraction in order to assist or signify finger movements in stroke patients, deliver natural skin feedback during various scenarios in Virtual Reality games, and communicate noiseless Haptic Navigation signals on the wrist. Lastly, all the mentioned application areas are evaluated in Chapter 3 where we choose to explore the area of learning exercises in detail.

Chapter 3

Evaluation of application areas

This chapter investigates the suitability of Springlets in the application areas such as Stroke Rehabilitation, Virtual Reality games, Haptic Navigation and Learning exercises. This chapter aims to choose one application area among the mentioned application areas to investigate in detail.

3.1 Evaluation of Springlets for Stroke Rehabilitation

We studied the feasibility of using Springlets to straighten a bent finger

Inspired by the work of Collins et al. [2005], we investigated the role of skin contraction in driving *kinesthetic* movements in the body with Springlets. The goal was to check if Springlets are strong enough to drive or assist simple finger movements or provide a strong cue towards finger movements. In our feasibility study, we targeted the index finger on the right hand to check if a bent index finger can be assisted to a straightened position by the Springlet (Figure 3.2).

The next step was to choose an appropriate design of the Springlet to support the straightening movement of the index finger. Hamdan et al. [2019] discusses two approaches of achieving skin actuation using Springlets - The Directional Stretcher and the Pincher. The Pincher pulls the skin from both ends of the springlet towards the center of the springlet while the Directional Stretcher generates a one-sided skin-stretch (Figure 3.1).

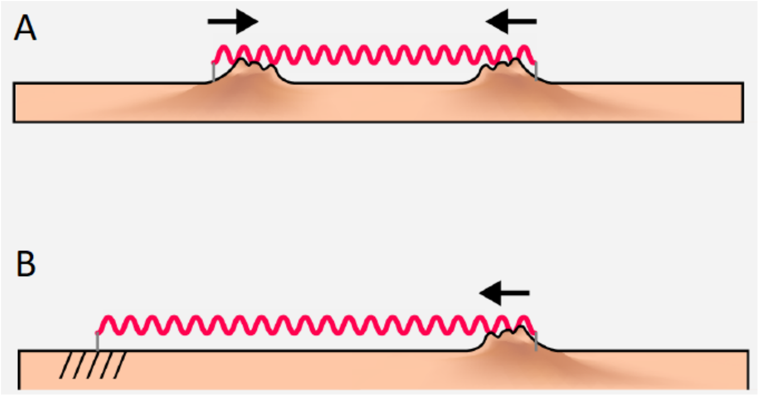


Figure 3.1: **A** : Operation of a pincher springlet. **B**: Operation of directional-stretcher Springlet. [Hamdan et al., 2019]

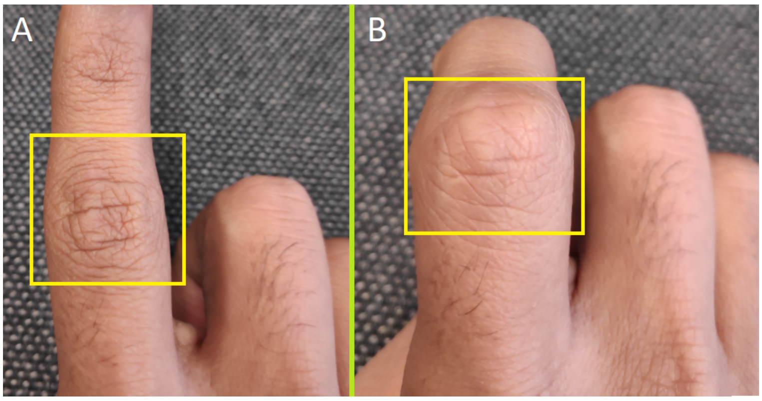


Figure 3.2: **A**: Straightened index finger highlighting the contracted skin pattern on the middle joint. **B**: Bent index finger highlighting the stretched skin pattern on the middle joint

We examined the skin patterns of the bending finger

On closely examining the middle joint of the index finger, we found that the skin on both sides of joint come closer towards the joint when the finger is straightened and goes apart on both sides when the finger is bent (Figure 3.2). This behaviour closely resembles the operation of a

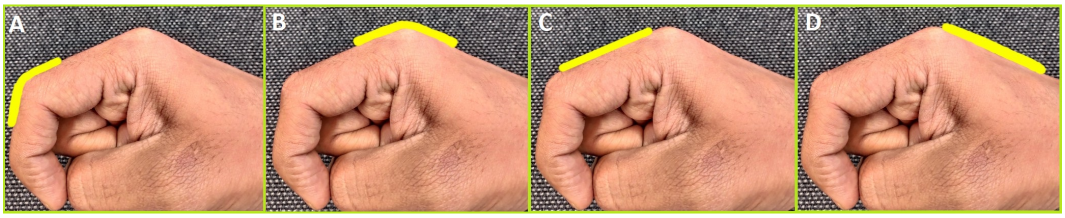


Figure 3.3: **A**: Highlighted position of the Springlet in the first attempt. **B**: Highlighted position of the Springlet in the second attempt. **C**: Highlighted position of the Springlet in the third attempt **D**: Highlighted position of the Springlet in the last attempt

Pincher Springlet and hence we decided to go further with a Pincher Springlet. It was now necessary to decide the position of the Springlet to ensure an efficient finger movement. The palm-side of the index finger was ruled out for the positioning as it would hinder the bending movement, cause discomfort on the palm due to heat, and could damage the topology of the SMA.

Springlets were affected by the topological changes of the finger

The springlet was initially chosen to be placed directly onto the middle joint of the index finger (Figure 3.3 A). However, it was found that this position was not effective in straightening the finger or providing straightening cues due to change in topology of the index finger while bending and straightening the finger. In the second attempt, the Pincher was placed on the bottom joint of the index finger (Figure 3.3 B) but it was still inefficient in generating finger movement cues because the minor topological change of the finger was still nullifying the effect of the Pincher. In the third attempt, the area between the middle joint and bottom joint was chosen (Figure 3.3 C) as this area doesn't suffer from topological changes during the bending movement. However, the length of the area was quite low to generate a noticeable pinch. This was mainly because Springlets can only contract until about half of its length and this signifies that the amount of contraction would be quite low to be noticeable if the Springlets had a lower length. In the last attempt, the area below the bottom joint (Figure 3.3 D) was investigated. However, this area suffered from loose skin and contraction of the springlet did not provide any cues for movement.

Springlets did not work efficiently on a small area and on loose skin

3.1.1 Conclusion of the Evaluation

Stroke Rehabilitation was not explored in detail due to the observed problems

Springlets mainly suffered from problems such as topological changes on the joints, low space, and loose skin and hence could not offer an efficient operation to trigger movement in the fingers. Further, it was observed that while the strength of the Springlets could be enough to provide a cue for the finger movement, it was quite low to be able to assist finger movements even with the stronger versions of the Pincher. Due to these problems, the Stroke Rehabilitation application was not chosen to be explored in detail.

3.2 Evaluation of Springlets for Virtual Reality Games

We explored the usage of Springlets on the forearm and the wrist to generate immersive haptic experiences in VR games

We investigated the possibilities of making Virtual Reality (VR) an immersive experience using Springlets as a device to deliver natural sensations on the skin during a VR game. The first step was to check if Springlets could offer a similar haptic experience as described by Yamashita et al. [2018] (Figure 2.5) during a distant arm-stretch movement in a VR game. The idea was to arrange multiple Pinchers parallelly below the elbow region of the arm (Figure 3.4) and activate all the Pinchers during the arm-stretch movement in the game. This could enable Springlets to handle natural skin-stretch requirements of a VR game without using any complex setup. Further, we also conceptualized the idea of using Springlets on the wrist as an immersive experience for games such as Spiderman during a web-shooting sequence (Figure 3.5).

We explored the idea of placing Springlets on multiple body location to simulate getting shot in VR games

A quite common method to deliver haptic signals of getting hit by bullets in games is by using vibration units [Cohen et al., 2017]. But, the feeling of getting hit by bullets could feel more real if the sensation produced matched a quick-pinch sensation that stayed for a while before getting back to normal. This closely matched the operation of a Pincher Springlet and the idea was to have Springlets on multiple locations on the body and activate them during a bullet-shooting sequence in a VR game.

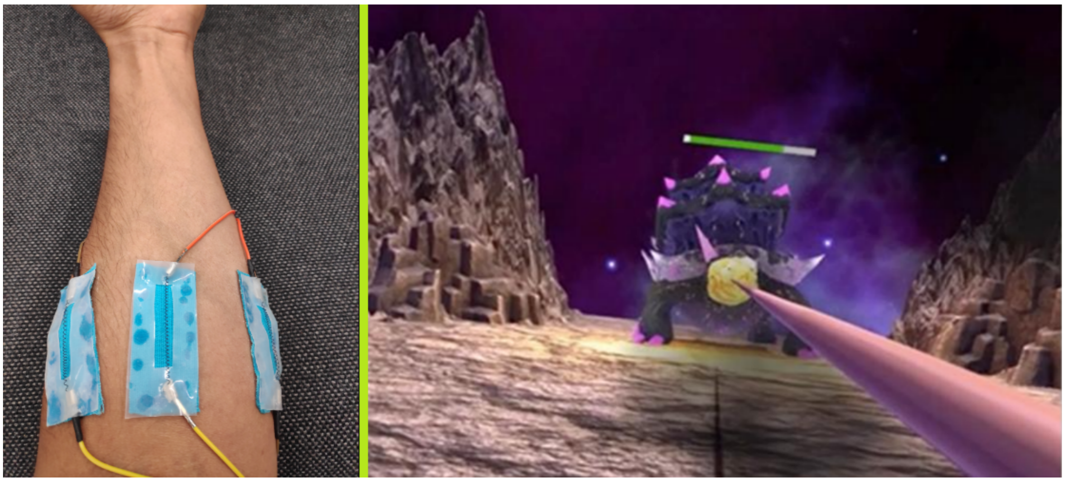


Figure 3.4: Left : Pinchers positioned parallelly on the arm to create long-arm illusion in VR games. **Right**: Visual arm-stretch experience in a VR game [Yamashita et al., 2018]

Figure 3.5: Left : Pincher on the wrist to create a haptic web-shoot illusion. **Right**: Visual web-shoot experience in the Spiderman game - Image credit: `http://createvr.com/spider-man-far-from-home` (accessed: 17.11.2019)

3.2.1 Conclusion of the Evaluation

Games are fast-paced but Springlets are slow

Games are usually fast-paced which means that Haptic devices need to react fast to create an immersive VR experience. But, we observed that while medium-sized Pinchers could contract almost instantaneously on passing a high amount of current, they required at least 3 seconds to get back to the uncontracted state. This behavior was not compatible with most fast-paced VR games as Springlets could be actuated and released only once in about 3 seconds. Hence, the area of Virtual games was not chosen to be explored in detail.

3.3 Evaluation of Springlets for Haptic Navigation

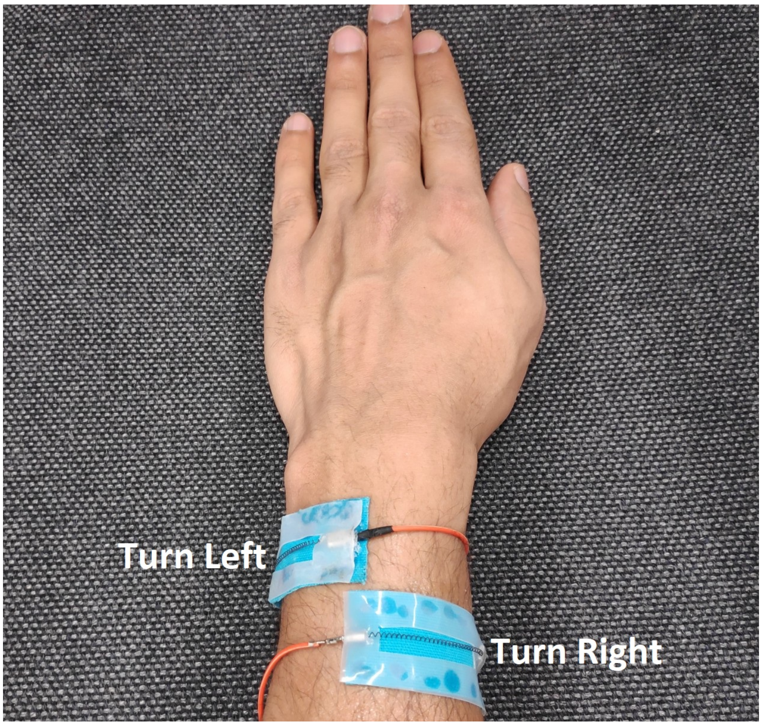


Figure 3.6: Two Springlets placed on the wrist to support turn-by-turn Haptic Navigation

We explored turn-by-turn navigation using Springlets

Inspired by the work of Dobbelstein et al. [2016] and Hamdan et al. [2019], we investigated the possibility of using Springlets as a Haptic Navigation device. The main idea was to place two Pinchers on both sides of the wrist (Figure 3.6) to deliver turn-by-turn navigation signals using skin-contraction. The obvious advantage over vibration units was that Springlets could deliver mild and noiseless haptic signals when compared to harsh vibrations originating from vibration units. We also conceptualized the positions of Springlets on other locations in the body such as upper-arm and shoulders to enable mild Haptic Navigation signals from Springlets hidden inside clothes.

3.3.1 Conclusion of the Evaluation

Springlets generate mild sensations and can fail in fast-paced navigation scenarios

Navigation devices are used in multiple situations such as travelling by vehicle or walking by foot. In both situations, Navigation involves mobility that is caused by movements of body parts. As Springlets deliver mild sensations, these sensations could go unnoticed frequently as Springlets are less noticeable in mobility situations [Hamdan et al., 2019]. Further, as Springlets are not compatible in fast-paced environments, they would fail in scenarios where there are multiple turns at low distances in the same direction as there would not be enough time for the Springlets to go back to the uncontracted state and contract again to signal a turn. Due to these inherent problems, the area of Haptic Navigation was not chosen to be explored in detail.

3.4 Evaluation of Springlets for Weight Training

Skin patterns on the arm allow the use of Pincher Springlets to guide arm movement

Collins et al. [2005] showed that it was possible to create movement illusions using skin-stretch. Moreover, Feygin et al. [2002] pointed out that Haptic Guidance was a good choice over Visual Guidance when the timing of the movement was important. This was the motivation to look into the area of guiding weight exercises as timing plays an important role in the effectiveness of exercises. The initial idea was to guide arm movements to train the Biceps muscle. The natural skin patterns on the region on the other side of the elbow (Figure 3.7) showed that the skin is stretched at this region when the arm is stretched and the skin from both sides of the arm shrink at the same region when the arm is bent towards the shoulder. The skin patterns closely imitated the operation of the Pincher Springlet.

Figure 3.7: Left: Skin patterns when the arm is stretched **Right**: Skin patterns when the arm is the bent towards the shoulder

Due to these skin patterns, skin-contraction seemed to be an better alternative when compared to one-sided skin-stretch described by Collins et al. [2005].

3.4.1 Conclusion of the Evaluation

Haptic cues from Springlets are noticeable and consistent with the nature of the weight exercises

During the feasibility study, we evaluated several positions of the Pincher Springlets near the region specified in (Figure 3.7) and we found that the haptic cues generated by the Pinchers were noticeable and could potentially serve as an arm-movement guide. The delay in the operation of Springlets was consistent with the fact that weight exercises are meant to be slow in order to be effective. As these factors pointed towards the effectiveness of Springlets as an exercise guide, we investigated various positions and designs of the Pincher Springlet in Chapter 4 to ensure its efficient operation as an exercise guide.

Chapter 4

Implementation of Springlets as an Exercise Guide

4.1 Design of the Exercise Guide

As skin patterns above the elbow during an arm movement suggested the use of a Pincher Springlet, the design of the Springlet to guide weight exercises was inherited from Hamdan et al. [2019].

4.1.1 Shape Memory Alloy

Spring-shaped shape memory alloy (SMA) is the core of a Pincher Springlet. On passing electricity, the SMA heats up and shrinks to about half its size (Figure 4.1). The shrink creates a pulling force at both the ends of the SMA towards the center of the SMA. However, to activate the shrinking process, the current passed must be greater than the threshold current of the SMA. The threshold current varies with different SMAs. Generally, the coil diameter of an SMA is directly proportional to the pulling force, generated heat and the threshold current.

SMA shrinks when a current greater than the threshold current is supplied

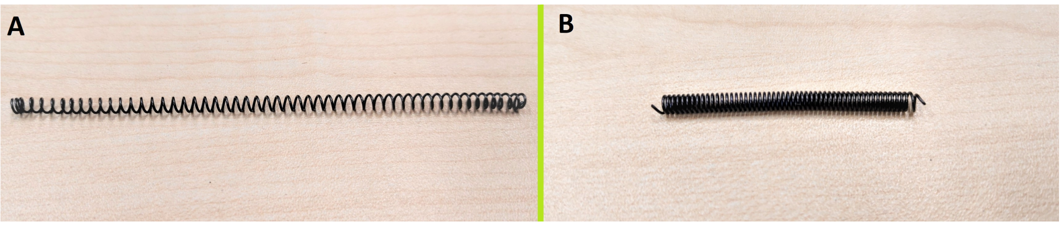


Figure 4.1: **A** : Stretched Springlet measuring 10.5 cm. **B**: Shrinked Springlet measuring 5 cm after passing current.

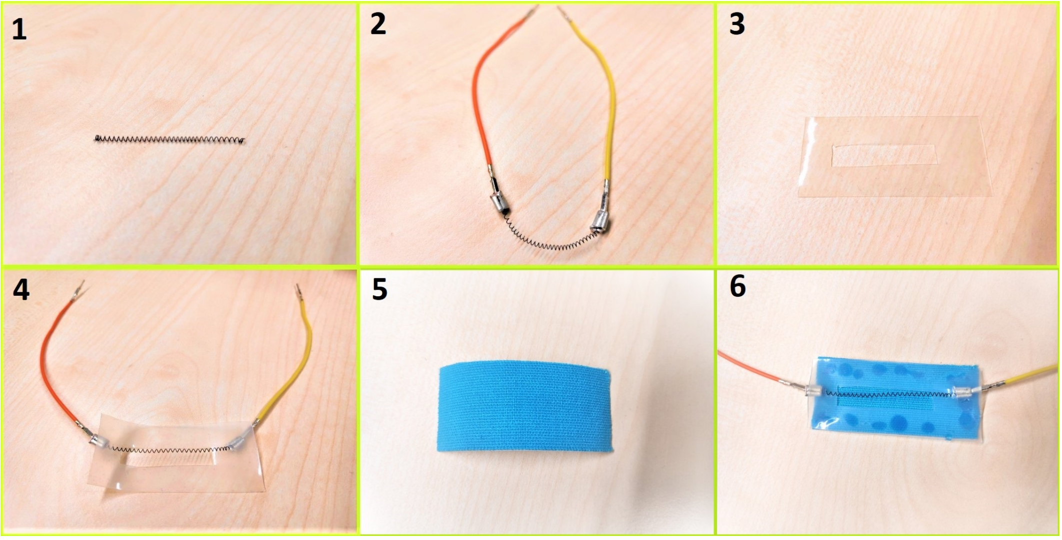


Figure 4.2: Pincher Springlet construction steps numbered from 1-6

4.1.2 Construction of the Pincher Springlet

We built Springlets using two functional layers with the SMA placed in the center

Hamdan et al. [2019] described the use of rapid-fabrication technique as a quick way to construct the Pincher Springlet using low-cost materials with three functional layers. We built a simpler version of the Pincher Springlet involving two functional layers namely the silicon layer and the kinesio-tape layer. Figure 4.2 shows the steps that were followed to construct the Pincher Springlet. The ends of the SMA were first crimped to electrical wires with male jumper pins. A rectangular layer of size 3 x 1 cm is removed from the center of a thin rectangular layer of silicon measuring 6 x 2.5 cm. Both the male jumper pins connected to the ends of the SMA were then pierced into the ends of the rectangular layer of silicon keeping the SMA in the center of the silicon layer. Finally, the rectangular silicon layer with the SMA was then pasted to a layer of Kinesio tape of the same size completing the construction of the Pincher Springlet.

4.1.3 Pincher Designs

As the Pincher Springlet was aimed to guide arm movements during Biceps training, we investigated several designs of the Pincher Springlet to improve the movement cues generated by the Pincher before finalizing the design mentioned in (Figure 4.3 D).

Large Pincher

Figure 4.3 A shows the initial design of the Pincher Springlet. This design was made of a large SMA so that it could generate a stronger pinch leading to stronger movement cues for the exercise movement. However, while the Pincher generated a strong pinch, it generated a a lot of heat and was consistently peeling off from both the ends during the contraction of the SMA.

Large Pincher generates a lot of heat and it peels off easily

Wide-Ended Large Pincher

There were hardly any movement cues from the first design because of the SMA getting peeled off at both the ends mainly due to strong forces of the large SMA. To solve the peeling issue, we changed the design of the Pincher as shown in Figure 4.3 B. The ends of the Pincher Springlet now were more wider than before resulting in a good grip at the ends of the SMA. However, the result was that the "Pinching" sensation quickly turned into "Pulling" sensation from both the ends because the ends covered a larger area of the skin.

Wide-Ended Pincher resulted in a pulling sensation at the ends rather than a pinching sensation

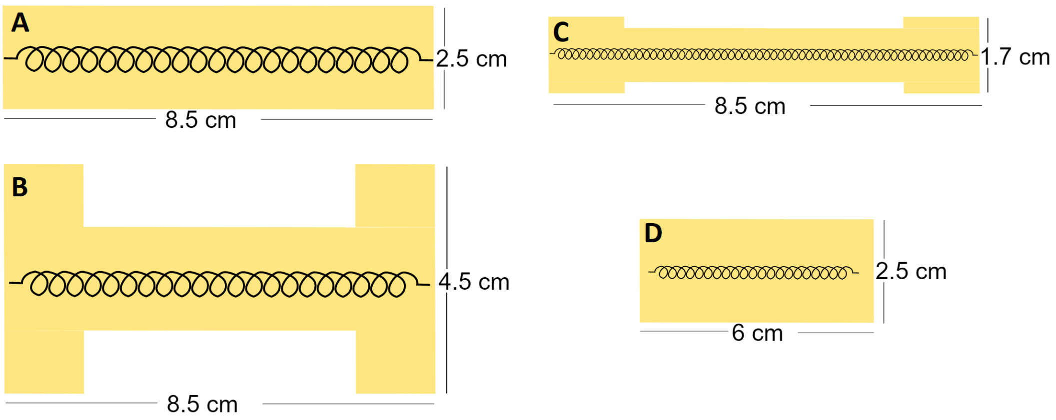


Figure 4.3: Investigated Pincher Springlet Designs

Thin-Base With Medium-Sized Pincher

Thin-Base Pincher resulted in a pinching sensation but did not cover a wide area on the skin

In order to keep pinching sensation intact with a good grip at the ends, the width of the ends were reduced (Figure 4.3 C) when compared to the Wide-ended Large Pincher Design. This resulted in better grip at the ends when compared to the Large Pincher Design and also resulted in more of a ”Pinching” sensation rather than a ”Pulling sensation”. Also, this design incorporated a medium-sized Pincher to solve the heat problem from the Large Pincher Designs. To increase the Pinching feel without overloading the medium-sized Pincher, the width of the base was reduced to 1.7 cm. However, while there was higher amount of Pinch, the Pinch was not strongly felt as the SMA covered a large but not wide region on the skin. Also, there was still some amount of pulling sensation at the ends as the ends were still a little wider than the main base of Springlet.

Short and Wide Base With Medium-sized Pincher

Changes in skin patterns are at peak near the elbow. Hence, a large Pincher was unnecessary

As the Pinch was not strongly felt in the Thin-Base design, the new design (Figure 4.3 D) incorporated a wide base similar to the Large Pincher design. As the changes in skin patterns during an arm movement occur in the region closer to the elbow joint, the large length of the Springlet was unnecessary and hence the length was decreased to 6 cm. To solve the minute "Pulling" sensation near the ends of the SMA, the width of the ends were not changed when compared to the width of the main base of the Springlet. As this would have recreated the peeling issue, the SMA was now attached to the base with a small amount of spacing from both the ends of the SMA. This ensured that forces were not high at the ends of the Pincher Springlet which ensured that the Springlets were not peeled off easily at the ends when they contracted.

Peeling was solved by spacing the SMA away from the ends

There were several advantages of this design over all the other designs. First of all, the "Pinching" sensation was high as the Pincher's length was small and hence the SMA was not overloaded and could efficiently contract. Secondly, the Pincher occupied a wide region on the same area of the skin where the skin patterns change the most during an arm movement. Thirdly, the peeling issue was reduced from the initial designs while keeping the "Pinching" sensation intact. Hence, this design was finalized for the implementation of the Pincher Springlet to function as an exercise guide.

Short and Wide Base design has several advantages over other designs

4.1.4 Requirement of Multiple Springlets

Apart from the position of the Springlets, the configuration in which they were placed also had an important role to play. The initial trials showed that more than one springlet was required to function as a Biceps training Exercise guide. This was because Biceps training requires upward and downward movement of the arm and one Pincher could only guide the movement in one direction.

When the Pincher shown in (Figure 4.3 D) was placed on the arm and was activated by passing a current greater than the threshold current, it stretched the skin to generate a cue possibly signaling the upward movement of the arm. However, when the current flow was stopped, the Springlet went back to its unstretched configuration without generating any cue signaling the movement of the arm in the downward direction. In fact, one could not notice that the Springlet went back to its normal configuration as

One Springlet is insufficient to guide arm movement the skin on the arm got loose. This created the need to have a secondary springlet to guide the movement in the opposite direction.

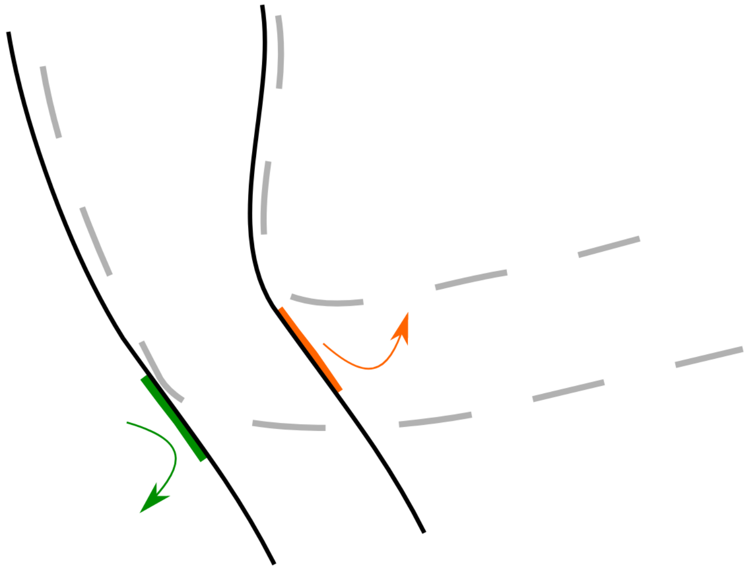


Figure 4.4: The arm movement pattern in a Biceps Muscle Exercise. The Springlet on the top (orange) guides upwards arm movement and the bottom Springlet (green) guides downward arm movement

4.2 Investigated Placement Positions

It was important to place the Pincher Springlets on the right positions on the arm so as to generate an efficient movement cue to guide the Biceps training exercise.

4.2.1 Elbow

The initial idea of choosing a position was an area on the arm where the skin stretches and contractions are at the maximum during a Biceps exercise. Hence, the chosen position on the arm was the elbow and the area exactly on the opposite side of the elbow (Figure 4.5). When the Pincher

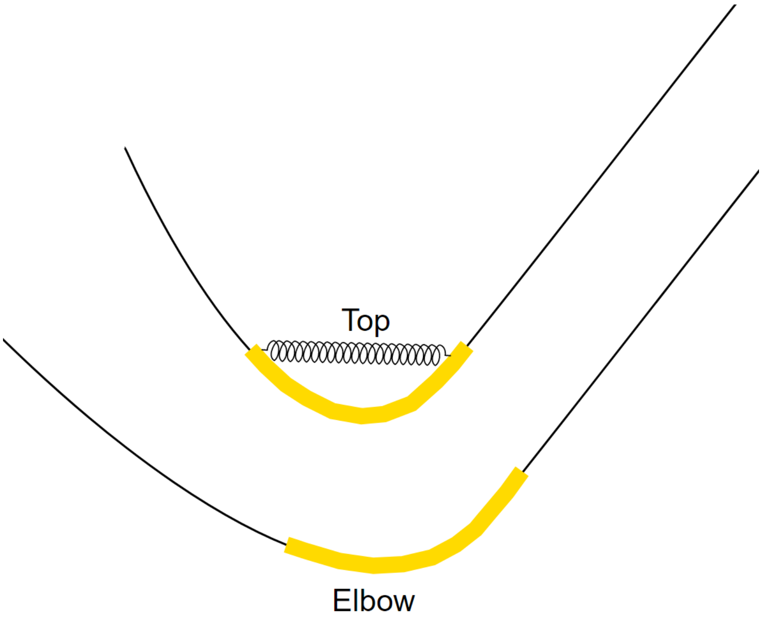


Figure 4.5: Springlets positioned on the elbow and above the elbow

activated on the top, it was observed that the SMA contraction did not create any haptic cue. This was because the SMA was not placed on the skin in a flat manner due to the topology of the arm near this area. As the base was not flat, the contraction of the SMA did not result in contraction of the skin (Figure 4.5). The SMA on the elbow was identically placed as the SMA above it. As this area also did not have a flat base, the contraction of the SMA on the elbow was not fruitful.

Springlet contraction on elbow did not contract the skin

4.2.2 Outer Side of the Elbow

To solve the problem of an uneven base, another region on sides of the arm was investigated (Figure 4.6). This region had a flat base as well as skin movements during a Biceps exercise. However, the movement of the arm created a sideways topological change in the base of the Springlet. Although the base was flat now, the contraction of the SMA still did not result in an efficient cue signaling arm move-

The outer side had a stable base but failed to produce a movement cue in a meaningful direction ment in a certain direction.

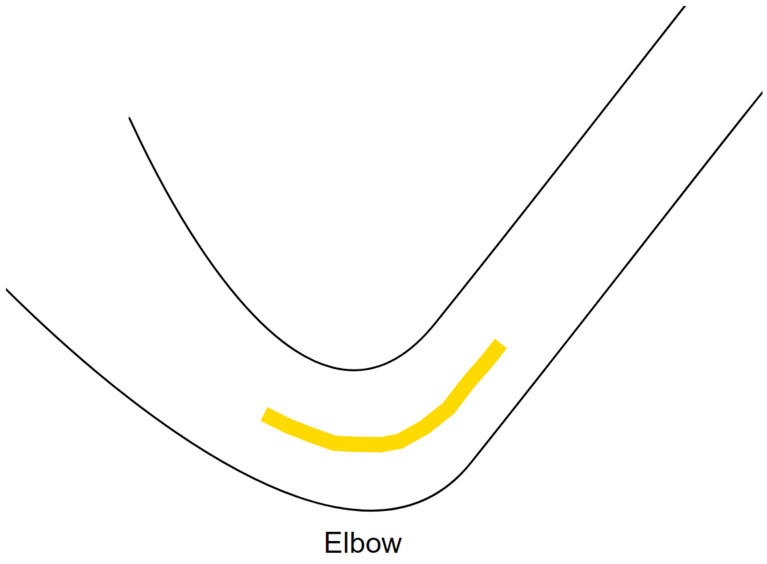


Figure 4.6: Springlets positioned on the outer sides of the elbow

4.2.3 Upper Forearm

Springlet on the upper forearm generated a strong cue to move upwards

Going further, the area on the upper forearm was investigated (Figure 4.7). The reason to choose this area was because this area had a flat base and was the closest to the elbow where the skin contractions are at the maximum during a Biceps exercise. When the SMA on the top area was activated to contract, it was observed that it generated a strong cue to move the arm upwards. This was mainly because the skin on this area is usually tight and when the SMA contracts, the pulling force is highly noticeable and can function as a strong cue signaling arm movement. Naturally, the direction of this movement must be upward backed by the fact that the skin patterns generated by the pincher imitates the natural skin patterns created during the movement of the arm in upward direction.

The secondary Springlet to generate cues for downward arm movement was identically placed near the elbow on the opposite side of the top springlet. The skin on this

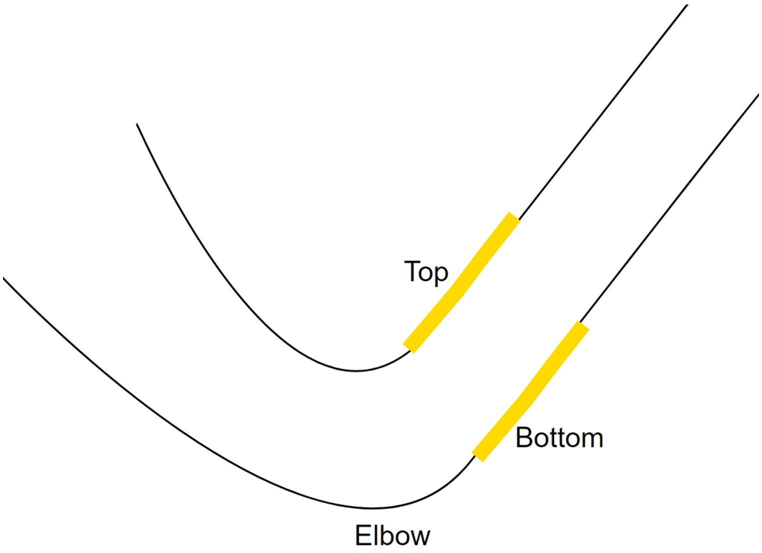


Figure 4.7: Springlets positioned on the upper forearm

area stretches when making an upward arm movement and contracts while making a downward arm movement. The placed on this area imitates the contracting skin pattern hence generating a cue for the downward arm movement. However, it was noticed this cue was less stronger than the cue of the top springlet due to lower changes in natural skin patterns during an upward and downward arm movement.

4.2.4 Upper Arm

On the upper arm, both the Springlets were effective

As a substitute to the placement of Springlets on the upper forearm, the placement of the Springlets on the upper arm near the elbow joint was investigated (Figure 4.8). The pinchers were placed in a similar configuration as on the forearm. It was noticed that the Pincher on the top generated strong cues for upward arm movement and the lower springlet generated a cue at a similar intensity for downward arm movement.

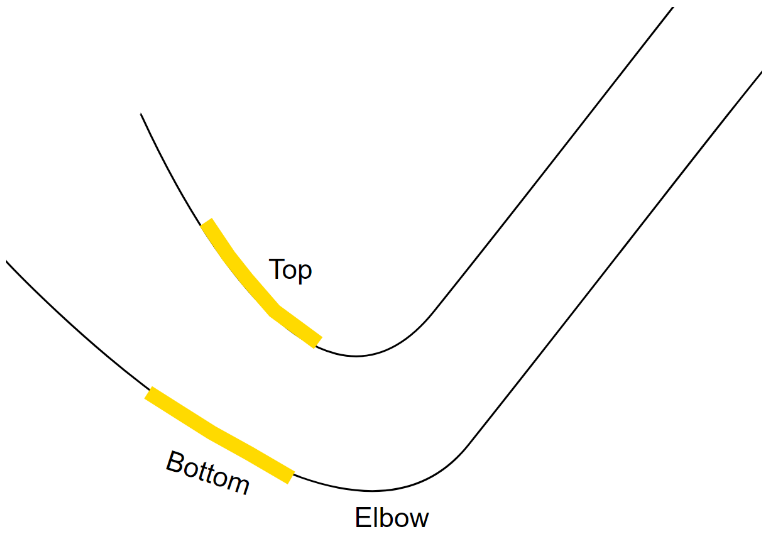


Figure 4.8: Springlets positioned on the upper arm

4.2.5 Selected Positions

From the investigation, it was clear that the Pincher Springlets were not efficient in generating cues on the elbow and outer side of the elbow. Hence, the Upper Forearm and Upper Arm positions (Figure 4.7 and Figure 4.8) were chosen to be studied in detail.

4.3 Operation of the Pincher as an Exercise Guide

4.3.1 Electronic Circuit

The electronic circuit is powered by an Arduino UNO, transistors and MOSFETS

Appendix A shows the Breadboard layout describing the electronic circuit that powers the Pincher Springlets to function as an exercise guide. The electronic circuit was built on top of an Arduino UNO microcontroller which is powered by 5V. The activation of Pincher Springlets was controlled using electronic signals from the Arduino board that travel through a 2N222A transistor and a IRF540N MOSFET connected in series. The transistor and MOSFET together act as a switch and disable the 6V DC power supply to the Pincher Springlets when there is no signal from the microcontroller.

4.3.2 Exercise Guide in Action

In order to guide the Biceps muscle exercise, two Pinchers were required to be placed on the top and bottom region of the upper forearm or upper arm. (Figure 4.9) shows an example of the required setup with one Pincher placed on top of the upper forearm and the other placed on the bottom of the upper arm. The Pincher on the top was responsible for guiding the arm upwards towards the shoulder and the Pincher on the bottom was responsible for guiding the arm downwards. The Pinchers together continuously generate cues for an upward and a downward arm movement required in a Biceps exercise.

The top Pincher drives upwards arm movement and the bottom Pincher drives downwards arm movement

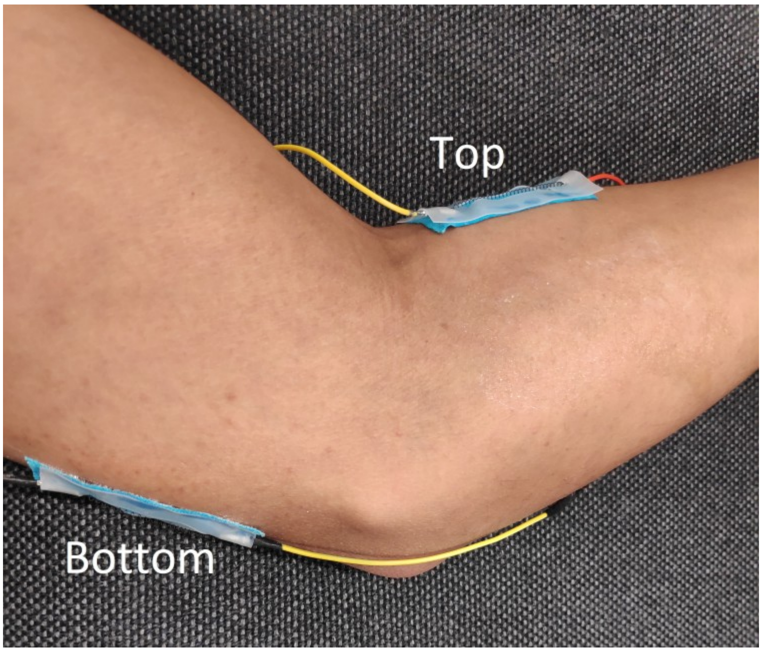


Figure 4.9: An example configuration of two Pincher Springlets to function as an exercise guide

The transistors drive the MOSFETs which finally activate the SMAs

To activate the Pincher on the top, an electronic signal is sent to the transistor from one of the analog pins on the microcontroller. This switches on the transistor and it allows the current from the external power source to flow to the MOSFET. This switches on the MOSFET which is capable of enabling a high current flow to the SMA embedded inside the top Pincher. This enables the top Pincher to contract the skin of the top of the forearm enabling the top Springlet to guide the upward arm movement.

The microcontroller was programmed to allow the current flow to the top Springlet for 3 seconds which is sufficient time for the top Pincher to contract. After this, a delay of 4 seconds was programmed following which the Pincher on the bottom is activated in a similar manner. This cycle continues with a delay of 4 seconds in between the cycles to allow the user to complete the arm movement.

4.3.3 Logging Arm Movements

Arm movements are detected through the accelerometer placed on the dumbbell

The electronic circuit also connects to an additional accelerometer placed on the dumbbell. The accelerometer was placed to track changes in the position of the arm during the user study. The microcontroller was programmed to read the position information from the accelerometer every 200 milliseconds and print it on the Serial port. Further, a simultaneous program running on the host machine continuously picked these values from the Serial port and recorded them into a file on the host machine with timestamps.

Chapter 5

User Study

5.1 Research Questions

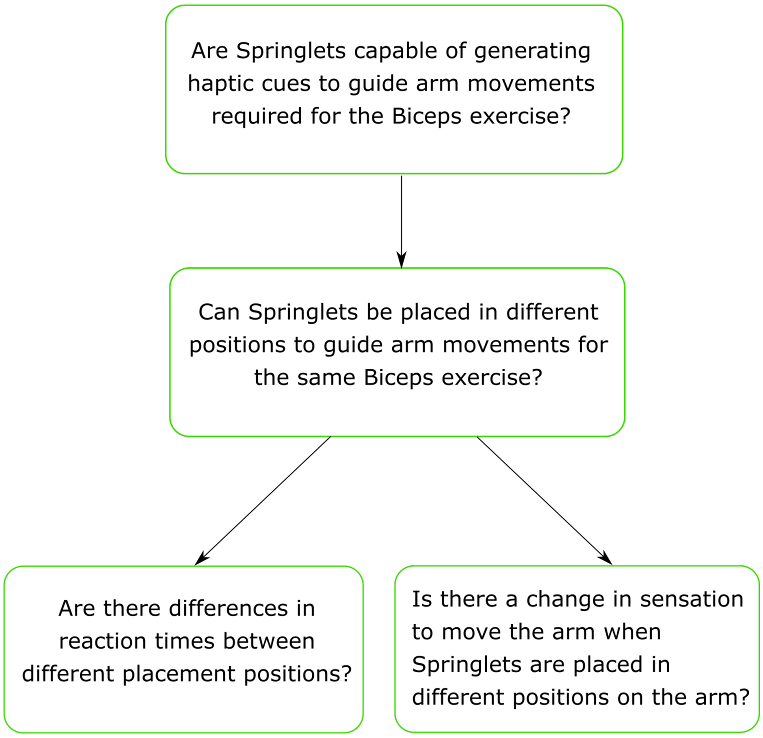


Figure 5.1: Research Questions

5.2 Hypotheses

Definition: *Hypotheses of the study*

HYPOTHESES OF THE STUDY:
H_0: The haptic sensations delivered by Springlets do not generate cues that signal arm movement for the Biceps exercises.

H_1: There is no difference in reaction times when Springlets are placed in different positions on the arm.

H_2: There is no change in sensation to move the arm when Springlets are placed in different positions on the arm.

5.3 Pilot Study

The pilot study involved two participants

We performed a pilot study with two participants before starting the actual study. The goal was to find deficits in the experiment setup. No problems were observed with the pilot study involving the first participant. In the pilot study involving the second participant, it was observed that the Springlet easily peeled off during the contraction of the SMA. Later, it was discovered that the participant had used a skin product that made the skin oily. Hence, it was concluded that oily skin could create problems and this was to be kept in mind while recruiting participants in the actual study.

5.4 Study Design

Diagonal placement gave rise to four Springlet configurations

From the previous investigations, we found that Springlets were efficient when placed on the upper arm and upper forearm. It was also interesting to see how Springlets perform when placed diagonally in both of these positions. This gave rise to 4 configurations (Figure 5.2) and the aim was to find out if there is a feeling to move the arm up-

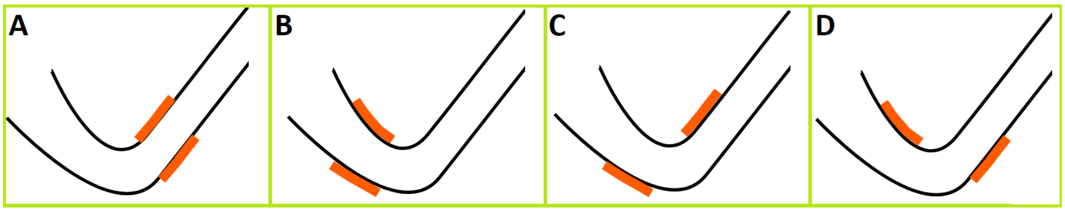


Figure 5.2: The four Springlet configurations for the user study. **A**: Top forearm, Bottom forearm (TFA, BFA) **B**: Top upper-arm, Bottom upper-arm (TUA, BUA) **C**: Top forearm, Bottom upper-arm (TFA, BUA) **D**: Top upper-arm, Bottom forearm (TUA, BFA)

wards and downwards in any of the configurations. We also aimed to find out which configuration among these configurations drives an easy understanding of the arm movement and also has a low reaction time.

5.4.1 Independent Variables

There are two independent variables in this study:

1. The direction of arm movement:
   (a) Upwards arm movement
   (b) Downwards arm movement
2. The configuration in which the Springlets are arranged:
   (a) **Top forearm, Bottom forearm (TFA, BFA)**: The upper Springlet is placed on the top of the forearm and the bottom Springlet is placed on the bottom of the forearm (Figure 5.2 A).
   (b) **Top upper-arm, Bottom upper-arm (TUA, BUA)**: The upper Springlet is placed on the top of the upper-arm and the bottom Springlet is placed on the bottom of the upper-arm (Figure 5.2 B).
   (c) **Top forearm, Bottom upper-arm (TFA, BUA)**: The upper Springlet is placed on the top of the forearm and the bottom Springlet is placed on the bottom of the upper-arm (Figure 5.2 C).

(d) **Top upper-arm, Bottom forearm (TUA, BFA)**: The upper Springlet is placed on the top of the upper-arm and the bottom Springlet is placed on the bottom of the forearm (Figure 5.2 D).

5.4.2 Dependent Variables

There are two dependent variables in this study:

1. Time taken by the participant to start an arm movement after the Springlet activates.
2. Likert Scale rating from 1-5 for questions regarding understandability and comfort for each Springlet configuration.

5.4.3 Study Type

A participant evaluated all the four Springlet configurations on a Likert Scale

The study followed a within-group design. Therefore, each participant completed the tasks for all the 4 Springlet configurations. The reaction time to make an arm movement was measured using the attached accelerometer while the participant performed the task for a particular configuration. After completing the task for a particular configuration, the participant rated the questionnaires related to the configuration on a 1-5 Likert Scale.

5.4.4 Latin Square Randomization

We randomized the order of the Springlet configurations

To ensure that the test results were not biased with the order in which the participants go through the Springlet configurations, we randomized the order of the Springlet configurations for each participant using the Latin Square technique.

Participant 1	1	2	4	3
Participant 2	2	3	1	4
Participant 3	3	4	2	1
Participant 4	4	1	3	2
Participant 5	4	3	1	2
Participant 6	1	4	2	3
Participant 7	2	1	3	4
Participant 8	3	2	4	1
Participant 9	1	2	4	3
Participant 10	2	3	1	4
Participant 11	3	4	2	1
Participant 12	4	1	3	2
Participant 13	4	3	1	2
Participant 14	1	4	2	3

Table 5.1: The order in which each participant goes through the Springlets configurations. The Springlet configurations are represented by digits 1-4.

5.4.5 Setup and Surroundings

The user study was conducted in a quiet room. The study did not take distractions into account as the primary aim of this user study was to identify if skin contractions using Springlets was capable of producing cues for arm movement. The setup (Figure 5.3) consists of a power supply connected to the electronic circuit. The electronic circuit controls the current supplied to the two Pinchers. The participant executes the study in a standing position, holding the dumbbell and making arm movements in an appropriate direction (Up and Down) when the appropriate Springlet activates. The connected accelerometer in the dumbbell keeps track of the arm movements and sends the data to the computer via the serial port.

The study took place in a quite room and the participant made arm movements in a standing position

5.4.6 Experiment Procedure

The user study took 60 minutes to complete per participant. The participant was first presented with an "Informed Study Consent" explaining the procedure and the

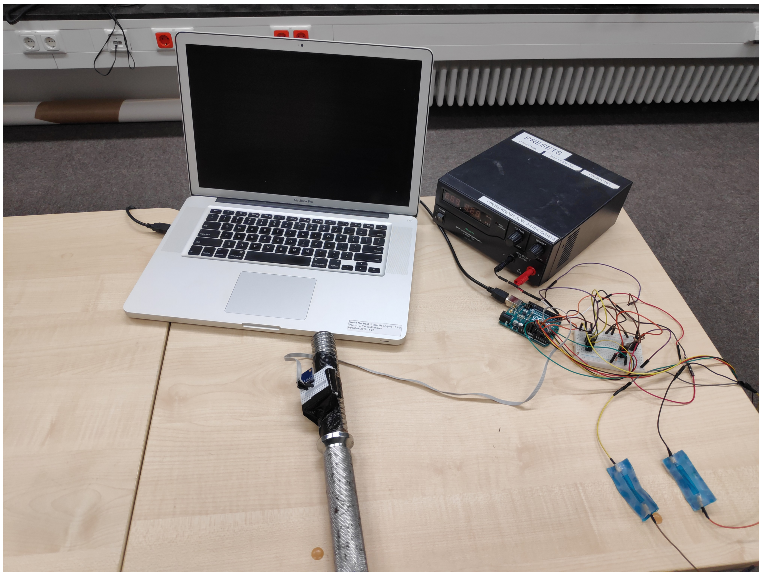


Figure 5.3: The user study setup

The participant started with filling out the Study Consent

risks involved in the study. After the participant signed the consent form, he was presented with a "General Questionnaire" which contained questions such as name, age, sex, arm length, and previous gym experience.

Participants went through trial rounds before the actual study and were asked if they sensed any motivation to move their arm

Before proceeding with the actual study, the participants were given a feel of the actual study by asking them to hold the dumbbell, attaching the Springlets participant's right arm and activating the electronic circuit so that the participant gets a feeling of the Springlets and the minor heat that they produce. Then, the participant was asked to imagine if the Springlets were trying to guide them to move in a particular direction, What direction would it be according to them? If the participant responded with the expected vertical arm movement pattern of the Biceps exercise, they were informed that we are studying the same movement pattern in this study. Otherwise, they were shown the vertical arm movement pattern for the Biceps exercise that is being studied as part of this user study.

Then the participant went through 4 rounds of the user study testing each Springlet Configuration. In each round, the participant was asked to make an arm movement in the expected pattern only when he feels the cue. The *mappings* of the upper and lower Springlets to the movement direction was not explained. During each round, the attached accelerometer on the dumbbell measured the reaction times.

The participant had to figure out the mappings by themselves

After each round, the participant was presented a questionnaire to rate the facts related to the last round involving one of the Springlet configurations.

5.5 Experiment Recordings

5.5.1 Videos

All the user studies were video recorded in order to draw retrospective observations from the user studies at a later point in time.

5.5.2 Reaction times

Reaction time is the time required to sense the Springlet actuation and accordingly make an arm movement. The reaction time was recorded for all the Springlet configurations in all the user studies.

5.5.3 Likert Scale Ratings and Rankings

The participants were presented with questionnaires after performing tasks for each Springlet configuration. The participants then rated the questionnaires from 1-5 on a Likert Scale. At the end of the study, the participant was asked to rate the Springlet configurations from 1 (best) to 4 (worst).

Participants evaluated the configurations using Likert Scales and Rankings

5.6 Participants

14 participants took part in the user study

A total number of 14 participants (13 Male, 1 Female) took part in the study. The average age of the participants was 26 (SD=1.84). The average length of the participant's right arm was 75.71 cm (SD=3.38). 9 out of 14 participants had previous experience with weight exercises.

5.7 Results

5.7.1 Statistical Tests

Repeated Measures ANOVA

Repeated Measures ANOVA test is applied on the data with reaction times

The Repeated Measures ANOVA test is run on the reaction times data to find out if there is a significant difference in reaction times among the four Springlet configurations and the test also checks if there is a significant difference in reaction times between the directions of arm movement (Up and Down).

Definition: *Null Hypotheses for Repeated Measures ANOVA Test*

NULL HYPOTHESES FOR REPEATED MEASURES ANOVA TEST:
H_{01}: There is no significant difference in reaction times among the four Springlet configurations.

H_{02}: There is no significant difference in reaction times between the directions of arm movement.

H_{03}: There is an interaction between the independent variables (The Direction and the Springlet Configuration), i.e. the direction variable affects the reaction time of a particular Springlet Configuration and vice-versa.

The preconditions to run the Repeated Measures ANOVA test are that data must follow a normal distribution and sphericity must not be violated. Shapiro–Wilk test for Normality and Mauchly's Sphericity test show that the input data satisfies these constraints and hence the Repeated Measures ANOVA test can be run.

MEANING OF SPHERICITY IN TERMS OF REACTION TIMES DATA:
Sphericity: Sphericity is not violated when the variances in terms of reaction times between all the possible groups of Springlet configurations are nearly the same [Yatani].

Definition:
Meaning of Sphericity in terms of Reaction Times Data

The Repeated Measures ANOVA runs once for the data with reaction times in seconds for the four Springlet configurations in both the directions of the arm movement (Figure 5.4). The level of significance (α) for this test is 0.05. The test shows that there is no significant difference (p= 0.86) between the reaction times among the four Springlet configurations. There is also no significant difference (p= 0.31) between reaction times with respect to the direction of arm movement. Additionally, no interaction effect (p= 0.66) between the independent variables (Direction and Springlet configuration) is observed. Hence, H_{01}, H_{02}, and H_{03} cannot be rejected.

No significant difference is found in reaction times among Springlet configurations

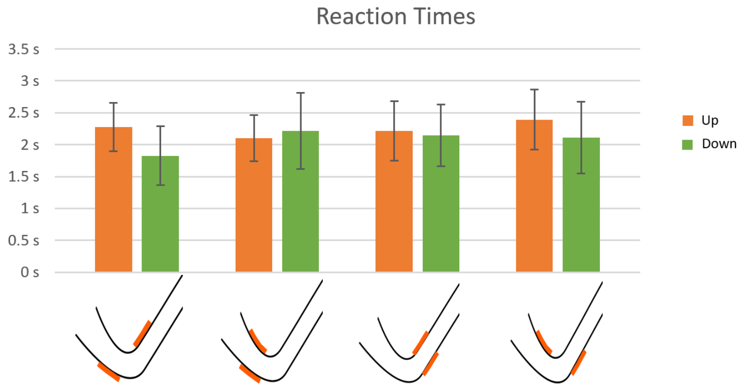


Figure 5.4: Graph denoting the reaction times in seconds (Y-axis) for the four Springlet configurations (X-axis). The orange bars denote reaction times for upwards arm movement while the green bars denote the reaction times for downwards arm movement

Friedman Test

Friedman test is applied on the data with Likert Scale questions

The Friedman test is run on the Likert Scale data containing ratings for various questions regarding noticeability, understandability, comfort, arm-movement motivation for all the four Springlet configurations. The test checks if there is a significant difference between the ratings for one question with respect to different Springlet configurations. This test is run 9 times for the 9 questions on the Likert Scale Questionnaire shown in B.3.

Definition: *Null Hypotheses for Friedman Test*

NULL HYPOTHESES FOR FRIEDMAN TEST:
H_{04}: There is no significant difference in Likert Scale ratings between all the four Springlet configurations.

Significant differences were found

The level of significance (α) for this test is 0.05. There were significant differences observed in ratings for 4 questions out of 9 (Figure 5.5) and hence H_{04} can be rejected for these 4 questions. The resulting p-values from the Friedman test are shown in C.1. There were significant differences between the following Likert Scale ratings:

1. Noticeability of the lower Springlet.
2. Motivation to move the arm when the Springlet activates.
3. Understanding of the arm movement when the lower Springlet activates.
4. Effort required to sync arm movements.

Friedman-Nemenyi Test

Friedman-Nemenyi test shows significant differences among two pairs of Springlet configurations

Friedman-Nemenyi test is run as a post-hoc test to identify the pairs of Springlet configurations where the significant difference in Likert Scale ratings lie. The level of significance (α) for this test is 0.05. Though the Friedman Test shows significant differences for 4 Likert Scale questions,

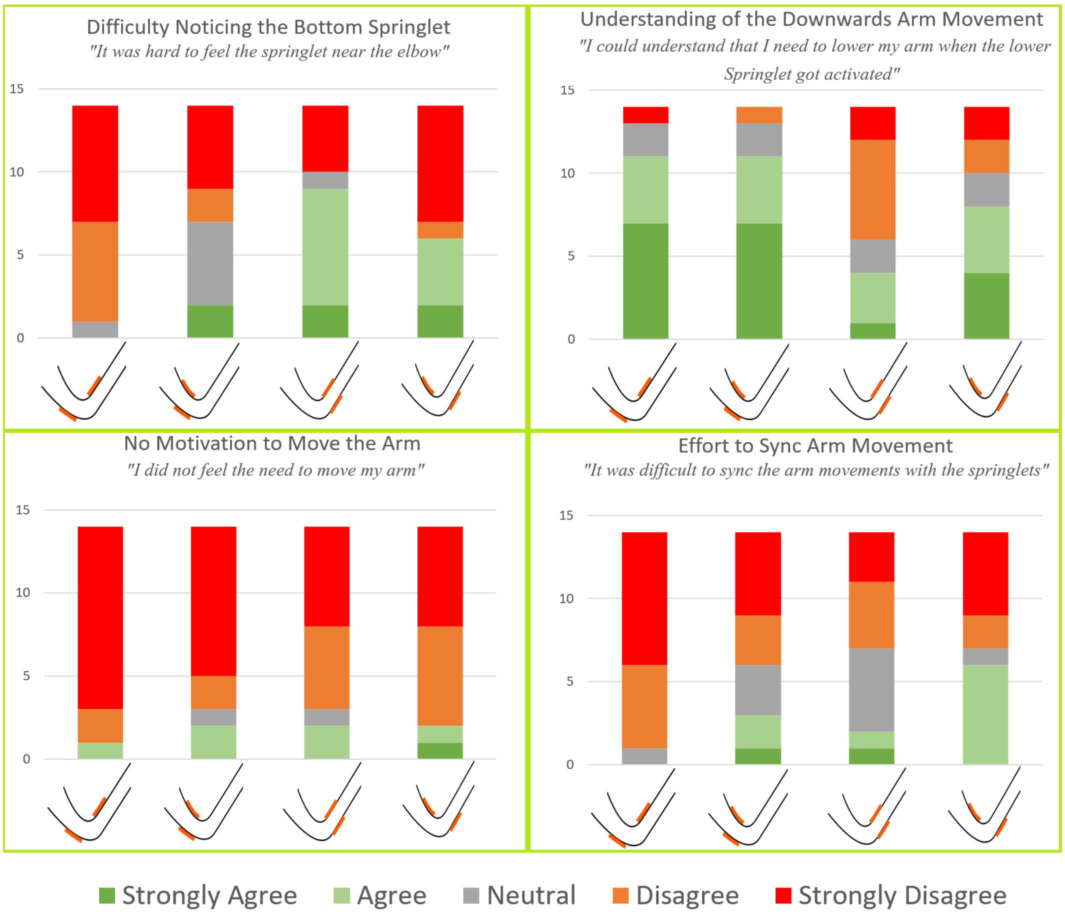


Figure 5.5: Graphs showing the visualization of Likert Scale ratings for the 4 questions with significant differences. Each graph denotes the different Springlet configurations along the X-axis and the distribution of ratings for a Springlet configuration by the total number of participants along the Y-axis. Graphs for other questions are shown in C.2

the post-hoc tests show significant differences among two pairs of Springlet configurations only for the question regarding "understanding of the arm movement" when the lower Springlet activates.

5.7.2 Rankings

At the end of the study, each participant was asked to rank the Springlet configuration from 1 (best) to 4 (worst). The results of the ranking are:

TFA, BUA is the best configuration based on the rankings

1. **TFA, BUA** configuration (best)
2. **TUA, BUA** configuration
3. **TFA, BFA** configuration
4. **TUA, BFA** configuration (worst)

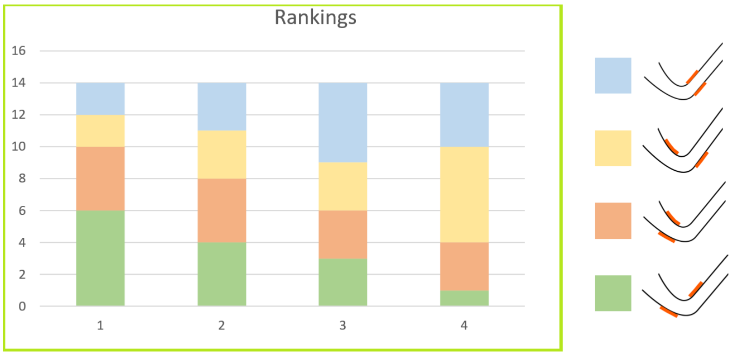


Figure 5.6: Graph denoting the rankings from 1 (best) to 4 (worst) along the X-axis and the distribution of a rank among different Springlet configurations by the total number of participants along the Y-axis.

5.7.3 Observations

The following observations are made from the statistical tests:

No significant difference in reaction times but significant differences observed in four Likert Scale questions

1. There is no significant difference in reaction times among the different Springlet configurations.
2. There is a significant difference in the ratings of the question that asks if it was hard to feel the bottom Springlet (p= 0.01).

3. There is a significant difference in the ratings of the question that asks if there was any motivation to move the arm when the Springlet activated (p= 0.03).
4. There is a significant difference in the ratings of the question that asks if there was any difficulty in syncing arm movements (p= 0.02).
5. There is a significant difference in the ratings of the question that asks if the participant could understand that he needs to move the arm downwards when the lower springlet gets activated (p= 0.002). Also, the Friedman-Nemenyi test identified significant differences only for this question.
6. The Friedman-Nemenyi test identified significant differences in terms of "understandability of the lower arm movement" in the ratings between:
    - (a) **TFA, BFA** configuration and **TFA, BUA** configuration (p= 0.02).
    - (b) **TFA, BFA** configuration and **TUA, BUA** configuration (p= 0.02).

5.7.4 Discussion

Springlets trigger movement cues

The main goal of the study was to check if Springlets can trigger movement cues. A significant difference in the mean ratings of the question regarding "motivation to make an arm movement" and the mean ratings of all the Springlet configurations hints at the presence of movement cues.

Participants had mixed reactions for different Springlet configurations

However, the movement cues were perceived differently among the participants. Many participants expressed during the study that the bottom Springlet was not quite noticeable when placed on the forearm. This was most likely because the Springlets were very close to the elbow and it was observed among participants that the elbow area was less sensitive to pinches than other areas of the arm. On the contrary, many participants also felt that movement cues were especially present in the TFA, BUA configuration

(*"Cannot ignore the feeling. It is mild but still makes me move my arm*: P7").

The next goal of this study was to find if there is a significant difference among the Springlet configurations in terms of multiple performance factors. The result of the Friedman test on the Likert scale data shows a significant difference in the ratings of the question that asks if the participant could understand that he needs to move the arm downwards when the lower Springlet gets activated. Out of the observations made during the study, this significant difference was likely due to the lower performance of the Springlet when placed on the forearm. The significant differences in other Likert Scale questions are also most likely due to the same reason which is hinted by lower mean ratings for the Springlet configurations that incorporate the bottom Springlet on the forearm (Figure 5.5).

Significant difference in Likert Scale ratings were mainly due to the lower performance of bottom Springlet on the forearm

Moreover, the significant differences in the Friedman-Nemenyi test and the observations from the study also point that the participants better perceive and understand the downward arm movement when the bottom Springlet is placed on the upper arm rather than the forearm. This is also supported by the higher mean ratings of the Springlets configurations where the bottom Springlet is placed on the upper arm (Figure 5.5).

Significant difference in post-hoc tests confirm the lower performance of bottom Springlet on forearm

While there are no significant differences in the Friedman-Nemenyi test that compares the upper arm and forearm positions for the upper Springlet, the user studies and the higher mean ratings on the Likert scale hint at better perception and understandability of the upper arm movement when the upper Springlet is placed on the forearm rather than the upper arm.

Forearm is a better choice than upper arm for the top Springlet

Interestingly, correlation tests revealed a positive correlation (r= 0.768) between the arm length and the reaction time in the TFA, BFA configuration (p= 0.001). However, this was found to be to inline with the theory that people with longer arms have higher reaction times [Brown et al., 2018].

Correlation tests suggest higher reaction time for longer arm lengths

5.8 Conclusion

As there is no significant difference between reaction times, H_1 cannot be rejected. Hence, the reaction times do not differ a lot among the different Springlet variants. However, variations are observed between the Springlet variants concerning other factors.

H_1 cannot be rejected as reaction times do not differ significantly

The result of the Friedman test on the Likert scale data shows a significant difference in 4 questions (noticeability, motivation, understandability, and effort to sync) out of 9 questions. From the discussion, it is evident that the significant differences in all questions are mainly due to low sensitivity of the bottom Springlet when placed on the forearm and the bottom Springlet performs better when placed on the upper arm. As the Likert scale ratings have significant differences for the questions related to "motivation to make an arm movement" and "understandability of the movement", we reject the H_0 and the H_2 hypotheses.

H_0 and the H_2 can be rejected

Further, the discussion also hints towards the fact the upper Springlet performs better on the forearm than the upper arm. Hence combining the results from the statistical tests, the hints from the study observations and the rankings, we conclude that the **TFA, BUA** configuration works best in terms of guiding the arm movement for the Biceps exercise.

TFA, BUA is the best configuration to guide arm movements for the Biceps exercise

Chapter 6

Summary and Future work

This chapter summarizes the thesis and proposes the possibilities of further work in terms of improving the existing system, extending the system and finding new application areas.

6.1 Summary and Contributions

We talked about various applications and shifted the focus towards tactile implementations

This thesis explored the usage of SMA-based tactile actuators in application areas such as Stroke Rehabilitation, Haptic Feedback in VR, Haptic Navigation, and Weight Training Guide. In the Related Work chapter, the focus shifted from traditional implementations to cutaneous tactile implementations in these applications which in turn depicted some advantages of the tactile implementations in the directional and temporal aspects of the interaction.

We studied the Weight Training application in detail

After conducting an evaluation of the four application areas and checking their feasibility with Springlets, the "Weight Training Guide" application was chosen to be explored in detail as the design of Springlets was a good fit in enabling Haptic Guidance of exercise movements while supporting the temporal aspects of the exercise movement.

Short and Wide-Base Design on the upper arm and forearm performed better than other designs and positions

After evaluating several iterative designs for the Pincher Springlet to function as an exercise guide, the "Short and Wide Base Design" was chosen as it covered a wide area on the forearm, also covering the area which is near to the elbow joint. This led to an efficient operation when compared to other designs. In the next step, the positions on the arm where the Pincher Springlets could be placed were evaluated and the upper-arm and upper-forearm positions were the best in terms of generating a cue for the vertical arm movement.

No difference was found in terms of reaction times but differences were found in terms of 4 performance factors

The statistical tests conducted after the user study found no significant difference in reaction times among the four Springlet configurations. However, they revealed significant differences among the four Springlets in the way they were perceived and understood. Gathering information from further tests and observation during the user studies, we concluded that the forearm region near the elbow was less sensible and hence was the reason for the significant differences. The observations and tests also pointed towards the fact that the upper Springlet functions best when placed on the forearm and the lower Springlet functions well when placed on the upper arm (TFA, BUA Springlet configuration).

6.2 Future Work

The thesis lays a foundation that can be extended

This thesis lays a foundation on tactile guidance techniques to train exercise movements. Hence, this work can be further extended to check the feasibility of more exercise movements, improve the SMA-based actuator for stronger movement cues, and explore more application areas for the SMA-based actuator.

6.2.1 More Exercise Movements

Exercise movements involve skin stretch and contraction

This thesis chose the Biceps Exercise movement to study the usage of SMA-based actuators to work as a Weight Training Guide. The SMA-based actuators are able to guide arm movements because of the skin contraction and stretching that occurs naturally near the elbow joint. However, skin contraction and stretching also typically happens at other joints in the body. Hence, the foundation of this work can be used to explore the feasibility of more exercise movements using Springlets.

6.2.2 Strong and Quick Actuation

There is a need for stronger and faster actuation in some scenarios

Although, the strength and speed of Springlets were sufficient to guide the Biceps exercise movement in most participants, exploring other exercise movements may require a faster and stronger skin actuation which is currently not possible due to the technological limitations of the Shape-memory alloy. Further research can look into improving the technology of the shape-memory alloy or exploring similar methods to achieve a natural but also a strong and fast actuation.

6.2.3 More Applications

More applications can be explored based on Haptic Guidance

This thesis explored the usage of SMA-based actuators for four application areas. Further research could look for more applications that can build upon the Tactile Guidance technique explained in this work. The ideas brought forward in this thesis can be combined with existing ideas to explore newer applications that ideally leverage the advantages of Springlets over other types of on-skin actuators.

Appendix A

Breadboard Layout

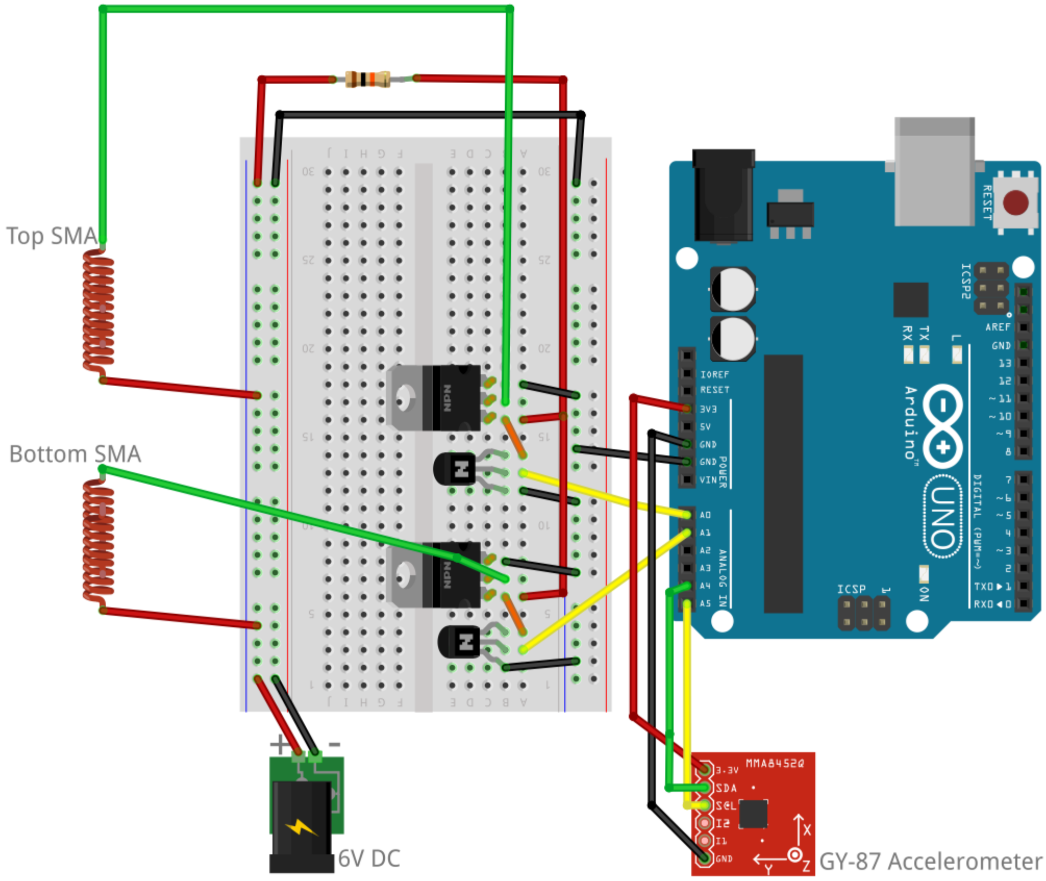


Figure A.1: Circuit Diagram (Created using Fritzing)

Appendix B

Study Consent and Questionnaire

B.1 Informed Study Consent

B.2 General Questionnaire

B.3 Likert Scale Questionnaire

Informed Consent Form

Evaluating the relation between skin contraction techniques and body movements.

PRINCIPAL INVESTIGATOR	Ajay Kumar Jha Media Computing Group RWTH Aachen University Email: ajay.jha@rwth-aachen.de

Purpose of the study: The goal of this study is to investigate the relation between skin contraction techniques and body movements. In order to do this, Springlets will be stuck to the arm of the participant and the resulting movements will be observed.

Procedure: Before the study, the participants are asked to fill out a questionnaire with some information about themselves. The study will be conducted in five rounds each round lasting about 2 minutes where in each round, the springlets will be stuck to a different position on the arm. The springlets will be stuck to the participants arm by the investigator and the springlets will be controlled by a microcontroller. The springlets will constantly contract and relax the skin during the study. After the end of each round the participants will be asked to fill a short questionnaire. This study will last about 35 minutes to complete.

Risks/Discomfort: The electrical components draw very less current and are well insulated. The spray that will be used to stick the springlets onto the skin is especially made for skin and is safe. Any discomfort or rash feeling on the skin can be immediately reported to the investigator. Springlets are shape memory alloys and they generate minor heat. If the heat causes any discomfort or becomes unbearable, it can be reported. In any of above cases, if the participant reports a problem, the study will be aborted immediately.

Benefits: The results of this study will help to understand the relation between skin contraction techniques and body movements.

Alternatives to Participation: Participation in this study is voluntary. You are free to withdraw or discontinue the participation.

Cost and Compensation: Participation in this study will involve no cost to you. There will be drinks provided for you during the participation.

Confidentiality: All information collected during the study period will be kept strictly confidential. You will be identified through identification numbers. No publications or reports from this project will include identifying information on any participant. If you agree to join this study, please sign your name below.

_____ I have read and understood the information on this form.

_____ I have had the information on this form explained to me.

Participant’s Name	Participant’s Signature	Date
	Principal Investigator	Date

If you have any questions regarding this study, please contact Ajay Kumar Jha at email: ajay.jha@rwth-aachen.de

Experiment Questionnaire

Evaluation of the relation between skin-contraction techniques and body movements.

Information about you:

1. How old are you? ________________

2. Please tick your sex ☐ Male ☐ Female ☐ N.A.

3. Have you ever been to the Gym or have any experience with weight exercises? ☐ Yes ☐ No

4. Do you have any skin abnormalities such as low-sensitive or hypersensitive skin? ☐ Yes ☐ No

5. If yes, name the skin abnormality? ____________________

6. Arm Length: ____________________

How well do you agree with the following statements? (First variant)

1. It was hard to feel the springlet on the top:

   Don’t agree — Fully agree

   ☐ **1** ☐ **2** ☐ **3** ☐ **4** ☐ **5**

2. It was hard to feel the springlet near the elbow:

   Don’t agree — Fully agree

   ☐ **1** ☐ **2** ☐ **3** ☐ **4** ☐ **5**

3. I did not feel the need to move my arm:

   Don’t agree — Fully agree

   ☐ **1** ☐ **2** ☐ **3** ☐ **4** ☐ **5**

4. The springlet on the top was comfortable:

   Don’t agree — Fully agree

   ☐ **1** ☐ **2** ☐ **3** ☐ **4** ☐ **5**

5. The springlet near the elbow was comfortable:

   Don’t agree — Fully agree

   ☐ **1** ☐ **2** ☐ **3** ☐ **4** ☐ **5**

How well do you agree with the following statements? (First variant)

6. It was hard to understand what the springlets where trying to communicate to me:

Don’t agree Fully agree

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

7. I could easily understand that I need to pull my arm when the upper springlet got activated:

Don’t agree Fully agree

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

8. I could easily understand that I need to release my arm when the lower (near elbow) springlet got activated:

Don’t agree Fully agree

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

9. It was difficult to sync the arm movements with the springlets:

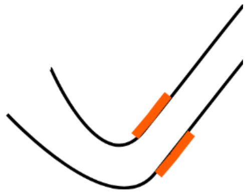
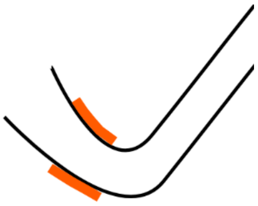
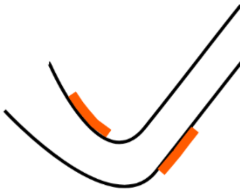
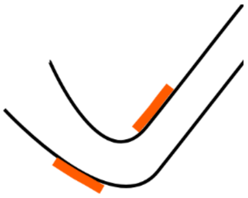
Don’t agree Fully agree

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

*** These 9 questions are repeated for all the 4 Springlet configurations ***

Ranking

1. How would you rank the variants?

Variant	Rank (1 to 4)
	
	
	
	

2. Do you have any thoughts about the suitability of Springlets to learn exercise movements? Also, suggestions for improvement or other comments (if any)

Appendix C

p-values and Graphs

C.1 p-values from the Friedman Test

	Question	**p-value**
1	It was hard to feel the springlet on the top	0.805
2	It was hard to feel the springlet near the elbow	**0.019**
3	I did not feel the need to move my arm	**0.036**
4	The springlet on the top was comfortable	0.614
5	The springlet near the elbow was comfortable	0.790
6	It was hard to understand what the springlets where trying to communicate to me	0.519
7	I could easily understand that I need to pull my arm when the upper springlet got activated	0.265
8	I could easily understand that I need to release my arm when the lower (near elbow) springlet got activated	**0.002**
9	It was difficult to sync the arm movements with the springlets	**0.021**

Table C.1: p-values from the Friedman test performed on Likert Scale data (Calculated using RealStatistics).

C.2 Graphs for Likert Scale Questions with No Significant Differences

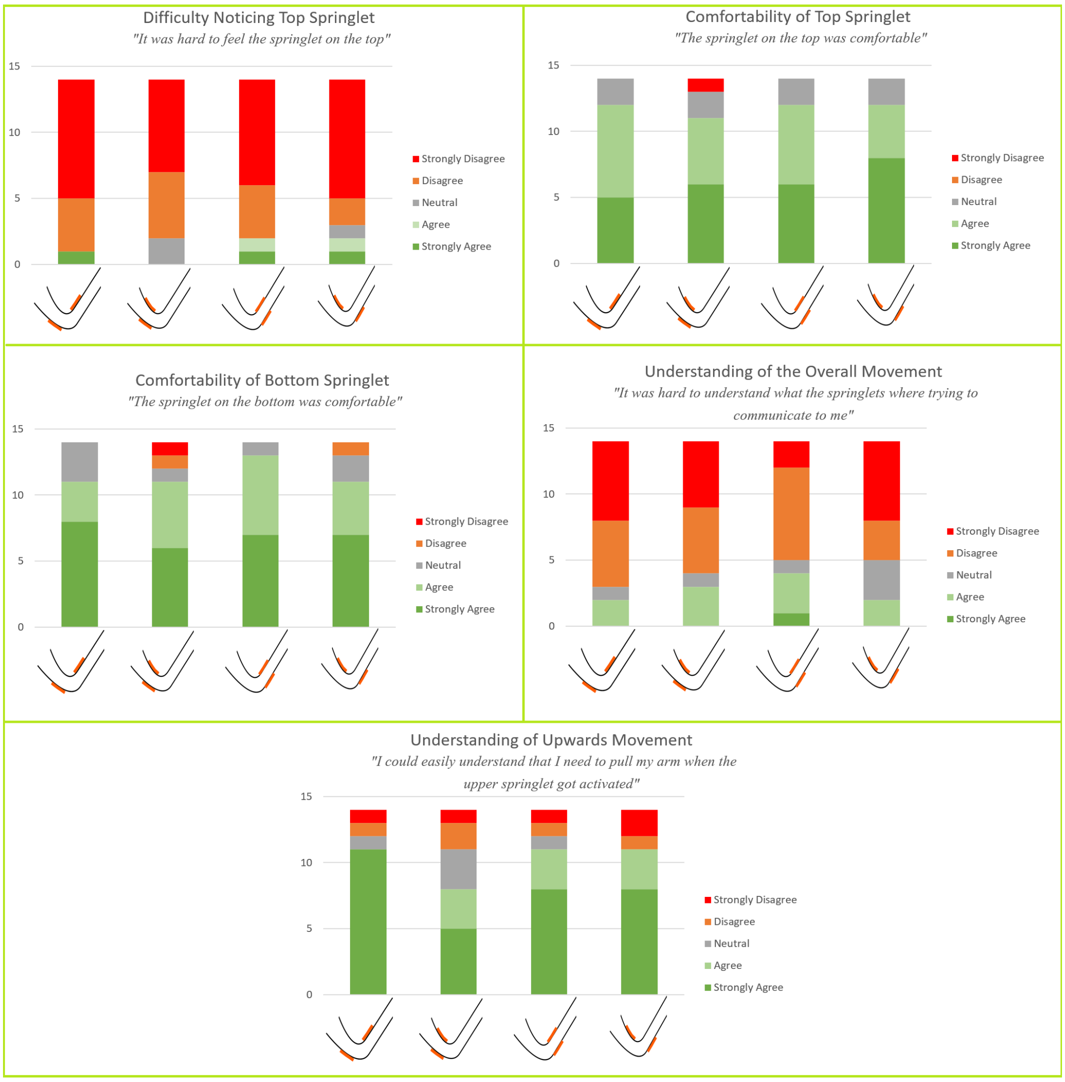


Figure C.1: Graphs showing the visualization of Likert Scale ratings for the questions that did not have significant differences. Each graph denotes the different Springlet configurations along the X-axis and the distribution of ratings for a Springlet configuration by the total number of participants along the Y-axis

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Typeset February 28, 2020