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Frozen Suit: Toward a Changeable Stiffness Suit and its Application for Haptic Games

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Figure 1. (Left) Frozen Suit can provide physical feedback in games by restricting users' movements, (Middle) for example giving the sensation of being frozen by an enemy. (Right) A jamming patch of the suit placed at a joint to restrict it.

ABSTRACT

We present the concept of Frozen Suit, a type of clothing that restricts users' movements at joint positions (e.g. elbow, knee) via a changeable stiffness jamming material. The suit can "freeze" users' body parts, for example during a game in order to provide the physical sensation of being frozen by an enemy. In this paper we first present the Frozen Suit concept and its potential applications. We then systematically investigate how to design jamming patches in order to sufficiently restrict an arm or a leg. In particular we used low-fidelity prototypes to explore the restricting power of different material and particles. In order to push this analysis further we conducted a controlled experiment in order to compare the perceived stiffness of different patches sizes attached to the elbow. We performed a paired comparison experience and used a Bradley-Terry-Luce model to analyze the subjective feedback from participants. We found that 20cm long x 7cm large is the most restrictive patch and that an increase in patch area correlates with an increase in perceived stiffness (quadratic). We finish by presenting a use case application with a game that we implemented where enemies can freeze the player.

Author Keywords

Changeable Stiffness; Jamming; Clothing; Wearable; Haptic Feedback; Paired Comparison Experiment.

ACM Classification Keywords

H5.2 [Information interfaces and presentation]: User Interfaces.

INTRODUCTION

Force feedback technologies have been proved to have numerous applications ranging from entertainment, medical or training scenarios [2]. In comparison to tactile feedback technologies they provide a wilder range of force and movements, thus producing proprioceptive feedback, i.e. the sensation or being pushed, restricted or moved. However force feedback systems are often cumbersome and hard to implement, as they often require complex mechanical actuators to provide desired strength [e.g. 2].

Smart fabrics that can change their stiffness in a controllable manner are a potential solution to this problem. In particular jamming mechanisms, using pneumatic actuation, are a promising solution as they produce great strength while being relatively small comparatively to mechanical actuators. Jamming is a technique used to change the stiffness of a material filled with particles. When inflated, the friction between the particles is low, allowing the particles to flow easily and the material to be soft. When deflated the friction between the particles is high making the material stiff. Jamming has been explored on tabletops and gloves [31, 11, 32] but exploration of a large form factors, e.g. a suit, is lacking.

We propose Frozen Suit, a suit with jamming patches at joint positions that can restrict users' movement. To enable the technology we first present our concept and highlight potential applications. We then systematically analyze how to design the jamming patches in order to provide enough strength. We built a series of prototypes having different properties (particles types, bladder material and size). We found that ground coffee was the most restrictive out of the particle types explored (granulated sweetener, flour, tea, ground coffee, instant coffee, tiny Styrofoam balls, and paper). We also found that elastic bladder materials, although they are good to produce jamming at a finger level, are too flexible to restrict efficiently larger limbs.

Our systematic exploration is followed by a controlled study in the form of a paired comparison experiment where we asked participants to rate between two patches the one being the most restrictive. We then used a Bradley-Terry-Luce model [25] to associate a “stiffness ability” metric to each patch. Our results demonstrate (1) not only it is possible to substantially restrict a participant’s elbow contrary to what as been suggested in prior work highlighting the limitation of jamming [32]; (2) but also that the size of the patches (area) correlates with perceived stiffness quadratically ($y=0.5017x^2-0.2351x-0.2691$, $R^2=1$). We finish this paper with a use case in the form of a haptic game where an enemy freezes the player.

RELATED WORK

Our work relates to force feedback devices used for body actuation as well as jamming interfaces. We choose not to cover actuation techniques used to trigger a range of tactile sensations such as soft pneumatic [14], actuated cloth [33], nor Shape Memory Alloys based devices [26] as those techniques are not strong enough to actuate body parts.

Force feedback technology for body actuation

Force feedback implies creating a directional force. E.g. articulated arms, such as the PHANToM [16], allow 3D force feedback. Although they are originally limited to pen interaction, they can be combined with intermediary objects to provide force feedback to other body parts. For instance in [27], a silicon layer is attached to the pen and placed on the top of a touchscreen. This allows creating a force feedback touchscreen that can actuate the users’ fingers.

One limitation of articulated arms is the creation of force feedback at a single point, while other systems offer multiple. For instance the SPIDAR system [28] uses motors in combination with multiple pulleys to actuate each finger independently. When all the fingers are attached, the system can be used to give the feeling to the users that they are manipulating a virtual Rubik’s cube displayed on a screen in front of them. This idea has been then reproduced for larger systems such as a canoe simulation [13].

Going a step further in term of user embodiment there are exoskeletons. For example gloves such as Cyberglove [15] or Dexmo [12] can lock fingers in certain positions. Motion guidance sleeve [7] is an external artificial muscle that creates a pulling sensation to guide users’ forearm. The system uses a combination of stepper motors, fishing lines and elastic bands to imitate muscle contraction. Beyond the hand and arm, there are also complex motion systems using a heavier mechanical platform to actuate the users [e.g. 2]. There is also a large portion of literature on prosthesis [e.g. 10] but we choose to restrict our survey as these devices rely on fairly complex actuation mechanisms.

Pneumatic devices

Jamming is a pneumatic actuation method providing restriction while being less cumbersome. Jamming is used to change the stiffness of a material and achieved by inflating or deflating a bladder filled with particles. E.g. it is used with particles [11] but also layers of paper [24]. When inflated, the friction between the particles is low, allowing the material to be flexible. When deflated the friction between the particles is high, thus making the material stiff.

Jamming emerged originally in the medical field where it was used as a portable emergency mattress (placed underneath a patient and then stiffen to carry the patient to safety). It had also been explored as a technique to make a flexible endoscope that can safely navigate a patient’s body [21]. Jamming has also been extensively used for creating robotics grippers [e.g. 5]. However, this mechanism has recently triggered the interest of the HCI community. In recent years it has been used as a technique to create shape changing interfaces, e.g. in Jamming Interfaces [11] or Claytric surface [23] where malleable tabletops with changeable stiffness are proposed (e.g. to mold an object).

Jamming has also been used in interactive gloves. In Exoskin [30], jamming is coupled with shape-change mechanisms to transfer the shape of an object to the hands of its wearer. The glove is demonstrated in the context of space exploration where wearing a thick space suit, although mandatory, suppresses haptic sensations with the environment. Simon et al. created a wearable jamming mitten [32] restricting users’ movement and imitating the sensation of grasping an object in a virtual environment.

While jamming has been explored as tabletops or gloves, there hasn’t been any exploration of a larger wearable form factor, such as a suit, which is the goal of our work. More importantly we did not find any literature evaluating the perceived stiffness/restriction from a user point of view. Our paired comparison study is thus the first of its kind.

FROZEN SUIT CONCEPT

Frozen Suit is a new type of clothing restricting users’ movements by using jamming patches at joints position. This concept opens new applications such as increasing realism in games, immersion of virtual environments or rehabilitation. We elaborate on the potential use cases of the suit, but first we give an overview of the system properties.

Suit principles

We discuss the ideal placement of the patches on the body before talking about the degrees of freedom of movement that they allow.

Placement of the patches

The Frozen Suit is formed of several changeable stiffness patches placed at several positions of the body. Figure 2 illustrates the ideal placements on a human body (green are the best positions, gray are unnecessary and red potentially dangerous). Since the human moves by inducing movements at the joints, placing the patches on non-joint positions (biceps or chest) will have limited effects on movements. However placing the patches on certain parts of the body could prove to be highly uncomfortable or might affect the wearer's balance. For example, restricting neck movement might negatively affect the user's fatigue as it might place him/her in an awkward position, causing it to become strained [1]. It could also be slightly dangerous. Additionally, restricting hip and feet movement could be dangerous if the jamming is activated while the user is in the middle of performing a certain movement as it might affect his balance. The most interesting parts of the body to consider restricting are thus the hands (including palm and fingers), wrists, elbows, shoulders, and knees.

Figure 2. Ideal placements of the changeable stiffness patches: green are the best positions; gray unnecessary; red potentially dangerous.

Degree of freedom

The Frozen Suit could also be formed of several changeable stiffness patches placed at a single location. Figure 3 illustrates such a case that could be useful to restrict joints in more than one direction. Typically the wrist could be locked in four different directions.

Additional tactile feedback

The gray parts of Figure 2 represent body parts that wouldn't work well for patch placement if the goal were to restrict movements. However these areas could be used for tactile feedback in other forms. For example, smaller patches could be placed on the chest to provide a different kind of feedback when jammed and unjammed (e.g. rapidly changing the stiffness of the patch could mimic being hit by bullets in a police training simulation).

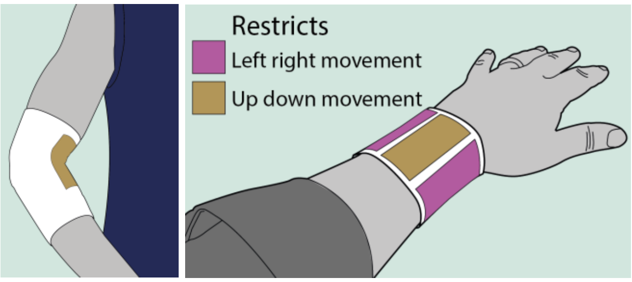

Figure 3. (Left) A patch can restrict movement of the elbow in one direction. (Right) Several patches could also be combined to provide restriction in several directions, here on the wrist to prevent left-right or up-down movements.

Applications

Haptic Games

We believe the Frozen Suit could be the next step towards increasing the immersion and realism of virtual environments (Figure 1). Such a suit is designed to be more portable compared to cumbersome systems using actuated arms. The suit would also offer substantially richer haptic feedback than the traditional vibrations based feedback systems, thus resulting in a more realistic experience (using the proprioceptive sensory system).

In particular: (1) the stiffness of certain parts of the suit could be changed to restrict (or free) the movements of the user. For instance the player could be "frozen" by an enemy, which would physically restrict the movements in the appropriate joints; (2) the suit can have a variable stiffness mechanism achieving a wider range of stiffness levels to simulate intermediate levels of movement restriction. For example, the suit could be used to implement a virtual underwater diving simulator and mimic the effect of being under water; (3) the suit can use stiffness activation patterns in order to create a more various range of haptic sensations. E.g. an ant crawling on the skin of the user in a virtual environment would have the same sensation while wearing the suit as it would in real life.

Figure 4. The Frozen Suit could be used for training. (Left) A golf player using a specific belt to train their posture. (Right) Simulation of military situations, e.g. fake an injury on a leg.

Training simulator

In the field of sports, the suit could be used for posture training. For example, in Figure 4, a golf player is using the 2XU Ramsay Posture Belt to achieve an ideal posture [17]. Such an application could be achieved with the Frozen Suit, as it can be jammed for a few seconds when the golf player achieves the proper posture if sensors are used to detect his movements and the positioning of his body. Jamming the suit for a few seconds before unjamming it again would restrict their movements at the ideal posture.

Additionally the suit could be used for job training to simulate situations. For instance, a soldier on field training could be in a realistic hostage situation where the suit offers realistic physical feedback such as limb injury. E.g. the suit could be used in combination with VirTra 300 LE [3], a police-training simulator having a real-time panoramic view. However, such a simulation has currently no physical feedback, something that can be achieved with the suit to provide a more immersive and realistic training experience.

Rehabilitation

The Frozen Suit could also be used for rehabilitation in orthopaedic and musculoskeletal therapies. E.g. on a leg it could help a patient to progressively control the extension of his/her knee while preventing rotational movements. Elderly people could also benefit from it. E.g. they could use it to overcome their muscle weakness when carrying shopping bags, or when trying to perform a simple task that old age has made difficult.

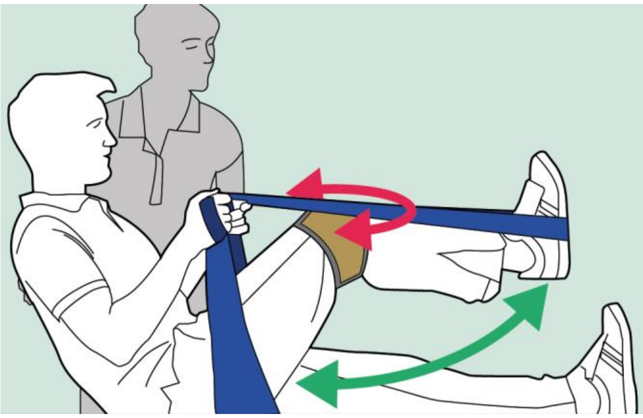

Figure 5. The Frozen Suit could be used for rehabilitation, here helping a patient to progressively control the extension of his/her knee while preventing rotational movements.

DESIGN RATIONALE

Although jamming interfaces have been explore in the past for tabletop or interactive glove, designing a system used for the body raise new challenges. In particular the strength of human muscle is relatively stronger than the one at the finger level. Additionally the size of the area to cover is bigger. In this section we systematically explore the design space of jamming patches by building prototypes with different properties (vacuum source, particles type, bladder material) and we then discuss their advantages and limitations. A table at the end of this section summarizes our findings (Figure 8).

Vacuum source

The common way to build a jamming system is to use pneumatic actuation using a vacuum source, generally an air pump. As describe in [11] pneumatic pressure directly relates to the magnitude of jamming. However there is not necessarily a linear relation between pressure and system stiffness. The actuation time is determined by the pump's flow rate. The time to remove excess volume from the bladder is determined by the amount of fluid volume, which needs to be removed to achieve jamming. There are several ways to improve actuation time and to precisely control the amount of air left in the bladder and these mechanisms are further described in [11].

For our exploration we needed a minimal system and opted for using a small air pump that would be suitable for portability (AIRPO D2028 12V air-pump). The pump has a vacuum range of 0-16" Hg and a pressure of 0-32 PSI. Note the creation of a mobile jamming system has external challenges not considered here such as self-contained wiring or energy sources and consumption.

Particles type

The types of particles (material, size and shape) also affect the restricting effect [21, 9]. E.g. coarse ground coffee has been shown to produce fast and stiff jamming while saw dust provide stronger forces in longer actuation times [9].

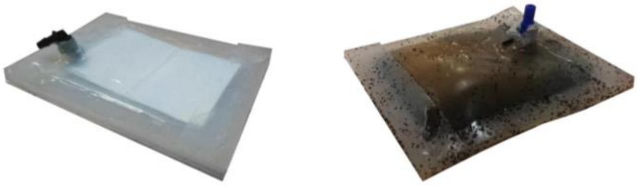

Figure 6. (Left) Paper filled patch vs. (Right) tea filled patch (both with silicon bladder).

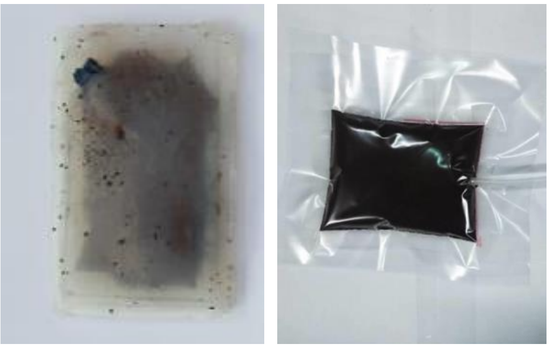

Figure 7. (Left) Silicon bladder vs. (Right) plastic bladder (both filled with ground coffee).

We tested several particles while keeping bladder material (silicon) and patch size similar. We tested seven different jamming particles: granulated sweetener, flour, tea, ground coffee, instant coffee, tiny Styrofoam balls, and paper (Figure 6). Our goal was to verify the coffee ground benchmark against common available particles.

Different particles experience different friction when the silicon patches are jammed (deflated). For example, having ten layers of paper allow reaching high stiffness and allow efficiently restricting the users when the bladder is deflated, but it didn't allow for much flexibility of movement when unjammed. Tea proved to be suitable for shape shifting applications where the silicon patch could take the form of different objects it is placed upon. However the particles seemed too soft and the tea filled silicon patches were not strong enough to restrict human movements, even slight ones. Other materials such as instant coffee, Styrofoam balls, flour and granulated sweetener were tested, but all proved not suitable for our particular jamming application. Coffee ground grains were thus confirmed to be the most restricting when jammed, while being flexible when unjammed, out of the particle types explored.

Bladder material

Another important element to consider when building jamming patches is the material of the bladder containing the particles. The bladder is usually a flexible membrane. Its thickness and elasticity vary between applications, and its quality affects the user's tactile experience as well as the performance of the jamming system in general.

We tested three materials while keeping particles type (ground coffee) and patch size similar. We evaluated latex, silicon and thin plastic (Figure 7). Silicon and latex have been widely used for jamming but we did not find them restrictive enough for our scenarios. Thing plastic offered a better restriction because it was deformable without being elastic. Even thick silicon patches were still not restrictive enough as the material was too elastic. We concluded that, although elastic materials are enough to produce jamming at a finger level, they are not adequate for larger limbs, and that thin plastic was the most adapted bladder material.

	granulated sweetener	flour	tea	ground coffee	instant coffee	Styrofoam balls	paper
rigidity when jammed	−	−	−	+	+	+	++
flexibility when unjammed	+	+	+	+	−	−	−−

	silicon	latex	thin plastic
rigidity when jammed	−	−	+
flexibility when unjammed	+	+	+

Figure 8. Summary of our investigations for (Top) the particle types and (Bottom) the bladder materials.

Summary

Figure 8 summarizes the advantage and drawbacks of the particle types and bladder material tested. Our explorations confirmed that ground coffee particles were the most restricting out of the materials explored. We found that thin plastic offered the most restrictive effect while being flexible enough when unjammed. Although we have been able to analyze the aforementioned properties via subjective testing, when we started testing the size of the patch, the differences in stiffness were too difficult to judge. We thus decided to gather empirical data to address this question. Our experiment is described in the following.

PAIRED COMPARISON EXPERIMENT

The goal of this study is to better understand the relationship between jamming patch size and their perceived stiffness. As this task is subjective in nature it was important to choose an adequate setup to gather the participant judgments. We opted for a paired comparison experiment, a typical study to gather Quality of Experience (QoE) feedback such as aesthetic or pain level. The study consists of asking participants to choose between two conditions, here to rate the most restrictive patch out of two. The experiment is designed so that each participant rates each possible combination of two conditions.

Pairwise experiments have been widely used in many fields of research. Estimating preferences of objects based on subjective judgements is a critical step in psychological experiments with applications in many research fields such as marketing, environmental sciences and health economics. Performing pairwise comparison ratings has been proven to produce more realistic results than asking for individual rankings (e.g. using a Likert scale) [4]. In particular there are mathematical models that can deduce an "ability" metric from the comparison data. In this paper we used a Bradley-Terry-Luce model [25, 6] to achieve this and to produce statistical ranking of the patches.

Participants

12 participants took part in the study. They were students in computer science from our institution and were not compensated for their time. Ages ranged from 24 to 29. Five of the participants were female.

Tasks

The participants were first given an overview of the project aims and an explanation of the experiment, along with a consent form. Next, they were asked to place two elbow supports to protect their arms from the vinyl tape used to secure the patches on their arms as shown in Figure 9. They were then asked to flex their elbows without moving their shoulders in order to familiarize themselves with the task to be carried out when the patches would be attached.

Figure 9. A patch attached to a participants arm. We used elbow supports to protect their arms from the vinyl tape used to secure the patches.

When the participants were familiar with the main task, two different sized patches were attached to the front of their elbows. Next, both patches were jammed and participants were asked to move both their arms in a flexing motion without moving their shoulders until they felt restricted. Participants had to state which patch between the two was more restrictive, or whether they were similar (Figure 10). Both patches were then removed, and the next two patches were attached. The procedure was repeated for all possible different comparisons of patches in order to compare each patch with one another.

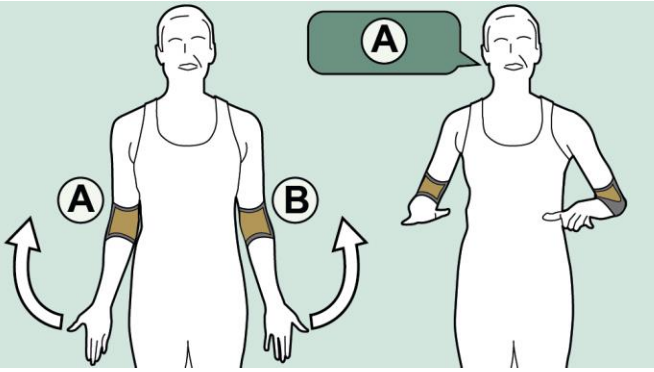

Figure 10. Illustration of the task performed.

Apparatus

We used jamming patches made of thin plastic for the bladder material and filled with ground coffee. We built four different patches including 2 heights x 2 widths. We choose the size based on the different patches created in the design rationale. 18-20 cm by 5-6 cm was a good compromise between strength generated and overall size (too large would hardly fit a suit). We used a scale (0.85g/cm2) to ensure that the density was similar.

Experimental design

Our experiment was a within subject one. We tested 4 patches including: 2 heights x 2 widths (Patch A: 18cm by 5cm, Patch B: 18cm by 6cm, Patch C: 20cm by 6cm, Patch D: 20cm by 7cm). The order in which the patches were compared together was determined by using a 6x6 Latin Square design, meaning only two participants out of the 12 started and ended with the same patch couples. The patches were placed on the user's elbow of a selected arm. For example, if the patch B was placed on the participant's right arm on the first time, it would, at one point of the experiment, also be placed on the participant's left arm. This was done to ensure that the participant's dominant arm did not affect the results of the experiment.

Additionally, even if a patch was to be used for two comparisons in the row, the patch was removed before being placed back on the participant's arm to ensure it didn't bias the participant's answers in any way. We also made sure that the ground coffee particles were equally distributed before starting a trial.

Results and analysis

Our analysis is based on [20] which suggests proceeding in three steps in order to analyze the results of paired comparison experiments. Note that to check whether our population sample was large enough, we looked at the observed power of our study. The power was .83, which is above the admitted threshold of .80 and indicates enough statistical power.

Step 1: Individual Consistency

In this step we tested if the participants were coherent within their answers. In particular we wanted to test the Transitivity Satisfaction Rate (TSR), which quantifies the consistency of a participant's judgments over m rounds in an experiment. E.g. if A is found more restrictive than B and B more restrictive than C then we should have A more restrictive than C. We implemented the algorithm described in [20] in Python to do so. Our results show that the TSR for 11 of our participants is 1, which is a perfect score. Participants 3 had a TSR of 0.7 showing some disagreement in the answers. This could be due to the fact that he felt that patches B and D were similar while all the other participants felt clear differences. In [20] the authors suggest 0.8 is a significant threshold for the TSR score however because all our participants had 100% agreement we decided to keep the participant 3 results as it was not too far from the 0.8 threshold. As shown below it does not affect the significance of our results.

Step 2: Overall Consistency

In this step we tested the overall consistency of judgments across different participants. This can be done by checking the stochastic transitivity properties or computing Kendall's u-coefficient. For each participant, we first computed a list of the ranking of the different patches (high perceived stiffness being ranked first). We then used the scipy.stats.kendalltau Python library to produce a Kendall's u-coefficient for each pair of participants. Our results show that the mean Kendall's u-coefficient is 91.4%, which is a very high value for overall consistency and demonstrates that participants are highly coherent among each other.

Step 3: Inference of a metric

The individual consistency and overall consistency were confirmed with high results, so in this last step we proceeded to model the data. One of the most widely used models for this purpose is the Bradley-Terry-Luce model [25, 6], which associates an "ability" metric to each condition that has been compared. To achieve this we used the BradleyTerry2 R package.

Note the Bradley-Terry-Luce model computes a p-value expressing how all the patches compare to one specific patch, which serves as reference and is a parameter of the formula. We thus performed several tests in order to compute the significant level for each pair comparison. To counteract the problem of making multiple comparisons tests we used a Bonferroni correction for each results described below with $p<(0.05/4)$.

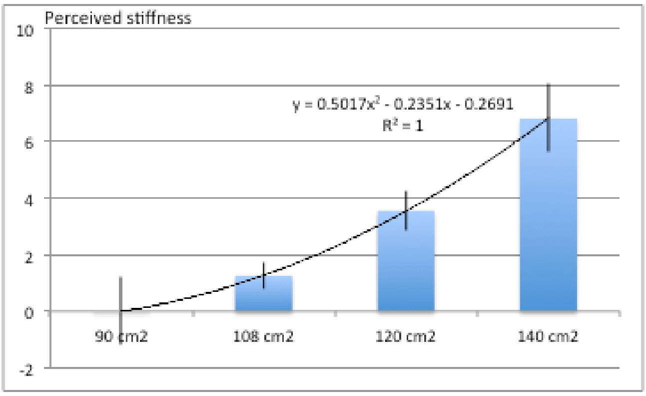

Figure 11. Bradley-Terry-Luce model output as well as a polynomial regression.

Our results are illustrated in Figure 11. We observed a clear distinction between the perceived stiffness of the 4 patches, the size of the patch increasing the perceived stiffness. In particular A is the least restrictive, followed by B, then C and then D is the most restrictive. We found that each paired comparison was significant ($p<0.0125$). This thus allows us to compare the different patches and conclude that D is the most efficient patch. We also performed a polynomial regression on our data and found a very accurate fit: y=0.5017x2-0.2351x-0.2691 ($R^2=1$). This suggests a quadratic correlation between the area of the patch and the perceived stiffness, which allows us to imagine bigger patches in order to restrict movements of the knee, which would require more stiffness. Of course further investigations need to be done to confirm this.

USE CASE: HAPTIC GAME

In order to demonstrate further the capabilities of the Frozen Suit we implemented a haptic game.

Game principle

Figure 1 shows the principle of the game for both virtual environments and classical displays. The game is set on a snowy island where the player fights ice enemies. There are two types of enemies in the game each with their own types of attack. The golem is capable of melee attacking the player, which is represented in the game by a flashing red screen, and the ghoul is capable of freezing the player. This results in jamming the elbows of the player thus restricting his/her movements and simulating the sensation of being frozen. There is also an additional visual effect displayed on the screen as well as an audio feedback. The player must hide away from the enemies in order to defrost. We used two remotes in each hand, as it is the set up used in many VR systems. Such a set up is also more desirable than a single controller as it allows users to control their avatar even when being "paralyzed".

Implementation

The game was developed using Unity. The different game mechanics and behaviors were achieved by using C# scripts. A script also allows controlling a wireless Arduino Yun Mini microcontroller acting as a communication proxy between the game and the jamming system. As it controls the air pumps, it uses the input it receives from the game to jam the patches when necessary.

Preliminary feedback

The game and jamming suit were informally tested in our lab. Although most participants showed excitement towards the concept of the suit and believed that the game had great potential, participants also highlighted some limitations.

First of all we could make improvement to the game itself. One participant mentioned attaching vibration pads to the hands to provide tactile feedback when the player fires. One suggested shaking the body to "break the ice". One suggested using the patches on the hand to prevent the player from shooting the fireball when frozen, thus forcing the user to hide for a while waiting for the patch to "defrost". Such a suggestion gave us additional game ideas where enemies are capable of targeting certain parts of the player's body. One participant said he could use the system for tennis simulation in order to help him doing appropriate movements when hitting the tennis ball. This corroborates our idea of the Frozen Suit used for other applications.

We also noted some limitation of the patches. E.g. the patch becomes less restrictive with time. This is due to the fact that the particles eroded in the bladder and split the bladder in two compartments over time. To prevent this, we could improve the patches by using a system of channels to keep particles flowing in specific part of the bladder. An initial implementation of this idea is further explored below.

Patch improvements with channels

As originally proposed in [30], it is possible to add channels to the jamming bladder in order to keep the particles at a specific position. This could be particularly useful when gravity is at play (the player is moving and thus the particles progressively fall in the same locations). Adding channels allows ensuring that the particles don't fall around within the patches, resulting in them always being distributed homogeneously within the patch. This means that the patch would not be affected by movements of gravity where the particles would move to one side of the patch, leaving the rest of it relatively empty, which happened when using simple rectangular patches.

Figure 12. (Left) Patch with channels (filled with flour for better visual). (Right) 3D printer mold used to generate the bladder with silicon.

Another important feature is that the channels allow for the patches to have directional flexibility (depending on the direction of the channels. E.g. the patch on Figure 12 is rigid in the horizontal direction, yet the space between the horizontal channels allow for flexibility in the vertical direction. Such intricate designs could be useful for various applications. For instance, it can be placed on the palm of a hand to restrict the fingers but not the thumb when jammed. We would like to explore this further in future work.

CONCLUSION AND FUTURE WORK

In this paper we have presented the concept of Frozen Suit, a haptic suit that can restrict the users' body parts using jamming mechanisms. Although jamming mechanisms have been explored in the context of handheld devices there are currently no exploration of large scale wearable systems based on jamming. In this paper we lay the foundations of such a system. In particular we found that current designs for handheld devices do not work for larger systems, as they do not provide enough strength. We have systematically explored the design space for building jamming patches for those systems. We found that ground coffee ground particles were the most restricting out of the particles explored (granulated sweetener, flour, tea, ground coffee, instant coffee, tiny Styrofoam balls, and paper). We also found, although elastic materials are enough to produce jamming at a finger level, they are not adapted for larger limbs, and that thin plastic is better suited. In a paired comparison experiment we evaluated the relation between patch size and perceived stiffness. In particular we found a quadratic correlation between size and stiffness. We then presented a use case scenario in the form of a haptic game where enemies can freeze players. We also present improvements of the patches to overcome gravity issues.

In future work we want to explore more intricate designs of the patch including different channels patterns and their effect on perceived directional stiffness. Additionally we want to explore how to provide different levels of jamming. Such a system would be capable of controlling the level of restriction that a user experiences and could be used in space and underwater simulations where different environment kinematic affects how a person's body moves. We also want to explore more tactile feedback such as designing thin jamming strips that can be jammed in a waveform and could be used to mimic the sensation of having an insect crawling on your arm.

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