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Actuating wearables for motor skill learning: a constructive design research perspective

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ABSTRACT
The integration of actuators into wearables to support haptic output and shape change provides an alternative to overused modalities like audio and video that allows a tighter coupling of feedback to body parts. Adopting a research-through-design approach, we report on six design explorations on how actuated clothing can support users to learn a movement skill, e.g. for sports or for the purposes of rehabilitation. Our exploration of actuation in wearables focuses on the aesthetics of form and of interaction, especially in relation to expressiveness and supporting how the user relates to other individuals. In this article, we discuss challenges and design potentials related to user experience and aesthetics of actuating wearables in this context.

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Introduction

More than 20 years have elapsed since Clothing+, a Finish smart clothing company, demonstrated the first heart-sensing T-shirt, and the interest in developing wearable technology for health and lifestyle applications has been growing steadily since. As argued in (Malmivaara 2009), designers and developers in this field face the triple challenge of creating clothing that is (a) comfortable enough to allow users to work as they normally would, (b) can constantly monitor their body in order to initiate appropriate action (c) is aesthetically pleasing. Here we examine this triple challenge for the design of intelligent clothing technology to support learning motor skills.

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Motor skill learning concerns the acquisition and refinement of motor skills, a core challenge in physical rehabilitation for enabling people to function in daily life, but also in sports for enhancing the performance of athletes. In neurological rehabilitation where, for example, stroke survivors re-learn to walk (Fung et al. 2006) or to use their arms and hands (Timmermans et al. 2009). Rehabilitation applications include the home monitoring of vulnerable patients (Patel et al. 2012), or even helping patients with lower back issues to improve their posture during daily life (Bootsman et al. 2019). In sports, they have been used for training elite athletes in rowing, table-tennis and biathlon (Baca and Kornfeind 2006).

A recent systematic literature survey in wearable rehabilitation technologies for the upper body (Wang, Markopoulos, et al. 2017) shows that most of this literature concerns the development and validation of wearable sensing technologies and only a few works focus on the output component of such system. Furthermore, movement feedback is typically visual with very few exceptions (11 papers in a period of 6 years) which involve actuation in the form of vibrotactile feedback (Wang, Markopoulos, et al. 2017).

Because actuation can support and guide user movement it is essential in robotic applications for rehabilitation, e.g. see (Laut, Porfiri, and Raghavan 2016) (Colomer et al. 2013). Such devices are intended for use in a fixed location such as a rehabilitation clinic. However, the need to support human capabilities in real life contexts, has fuelled the development of exoskeleton robotic devices, e.g. for the arm (Copaci et al. 2017), the lower limbs or the upper body or to support rehabilitation (Ding et al. 2013).

In contrast to rehabilitation robotics which is intensively explored the application of actuation to support rich interaction with wearable technology is relatively unexplored. Rich interaction is an approach to interaction design that respects the multiplicity of human skills (i.e. perceptual-motor, cognitive, and emotional skills) and aims for a unity of form, interaction, and function (Frens 2017). Supporting actuation on garments or light wearable appliances affords novel forms of interaction over and above audio and video modalities, which can be rich, aesthetic and unobtrusive. In this research, we explore the design potentials related to user experience and aesthetics of integrating actuation in clothing or discrete small body worn devices, of tightly coupling actuation to sensed movements of the relevant parts of the body and how its meaning can be contingent upon the placement of the devices on the human body and the correspondence of actuation to people's movements.

The following sections report on six design explorations aiming to:

1. Identify generic design challenges and opportunities that wearable actuation technology offers.

2. Expose design qualities of the proposed solutions and reflecting on their generic value to guide designers

Design potential of wearable actuation

A design-driven investigation of different actuation mechanisms in garments by (Toeters and Feijs 2014) explored the integration of, such as servo motors, voice coil actuators, shape memory alloys, in an attempt to make garments capable of displaying dynamic forms. They discuss numerous challenges for wearable actuation, such as concealing actuation components that are bulkier than sensors, powering these without compromising wearability, calibrating to the wearer, limiting the noise of motors which can compromise the intended aesthetics, etc. Their designs emphasised on the expressiveness of actuated garments which could display a defensive stance, attraction to another person, playfulness, the semblance of a breathing organism or to accentuate dancers' movements. Similarly the Kino toolkit (Kao et al. 2017) enabled design explorations with wearable kinetics, charting the possibilities of movement and shape change in wearables for self-expression, affective communication and as a personal notification display.

Haptics are directly applicable in clothing allowing system output to be experienced as haptic sensations on the skin. An early investigation identified four ways for varying vibrotactile feedback: spatial position change, speed of motion change, surface texture change, and force change (Poupyrev, Nashida, and Okabe 2007). He et al. (2015) describe 'PneuHaptic', a haptic interface that controls the inflation and deflation of an array of silicone air chambers, thus creating various sensations on the arm. 'Tickler' is a wearable tactile display consisting in an array of shape memory alloys, that are individually controlled to simulate stroking sensations (Knoop and Rossiter 2015). Bark et al. (2015) propose a wearable skin stretch device based on ultrasonic piezoelectric motor for haptic feedback regarding movement of a virtual object. Design researchers have also explored the hedonistic value of vibrations on wearables (Boer, Cahill, and Vallgårda 2017). Such works illustrate the wide range of possibilities for using haptics in wearables not only for functional purposes but also for their emotional and aesthetic aspects.

Haptic feedback for posture and movement

Haptics are particularly suited for supporting motor learning as they can be in continuous contact with the body, allowing output to be perceived in noisy environments or when visual attention is focussed on different tasks. While a high resolution visual display can be a richer medium for guiding motor learning, it may also put an excessive cognitive load upon users if they are expected to attend and interpret a screen while trying to learn a new skill and control their body (Zheng and Morrell 2010); it may also create distractions when visual attention is focussed on training tasks (Alahakone and Arosha Senanayake 2009).

Haptic feedback can be classified as tactile, kinaesthetic, and vibrotactile feedback (Alahakone and Arosha Senanayake 2009). Simple vibrotactile notifications can be slower to perceive and the resolution they offer is limited compared to the audio and visual modalities. On the other hand, they can be unobtrusive, delivered discretely, with only the user noticing them on selected body areas to provide an intuitive correspondence to the movement of the user. Vibrotactile feedback is used in commercial products such as the Lumo Lift™ (www.lumobodytech.com), which is designed to support posture monitoring, and correction. In neurological rehabilitation vibrotactile notifications have been used as a secondary display to notify users of deviations from an upright posture while playing a game that supports arm-hand skills training (Beursgens, Timmermans, and Markopoulos 2012). This notification is auxiliary to the visual display of training stimulus and feedback, limiting the demand visual attention of rehabilitating stroke patients.

For feedback not specific to a body part as for example in balance related feedback, sensor placement can be determined by ergonomic and aesthetic criteria. For example, (Benini et al. 2011) examined balance training for patients with damaged vestibular sense and found that vibration motors providing posture correction feedback are placed at the ankles where they can be hidden under clothing but still be noticed and interpreted reliably.

Position control and precise force are suitable haptic feedback strategies for rehabilitation applications. Causo et al. (2019) compared two vibrotactile feedback strategies: providing directional information or matching error (non-directional information). Their results suggested that non-directional feedback enables more accurate arm posture. Panchanathan, Rosenthal, and McDaniel (2014) developed a flexible vibrotactile strip that can be worn on the arm, providing vibration instruction for positioning and speed error through variations of a vibrotactile rhythm. Ding et al. (2013) also applied position and direction indication strategy by releasing different vibration patterns. Luster et al. (2013) used vibrotactile cueing to act as a reminder and a reinforcement for paretic arm use during the training practice of chronic stroke patients.

The works reviewed above emphasise the functional aspects and the effectiveness of haptic perception in the specific application context. Relatively less emphasis has been placed upon visual aesthetics, comfort and the integration of haptic output in wearables, which is the subject of the design explorations discussed in the next sections.

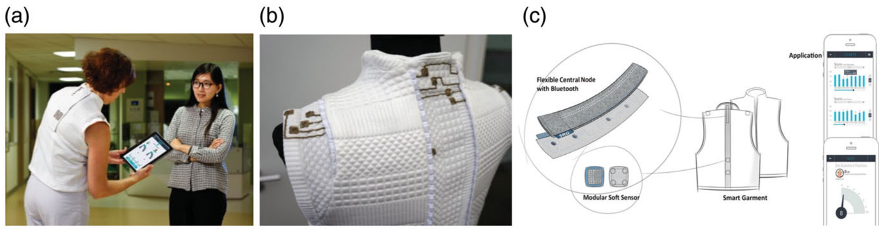

Figure 1. Left: A user calibrating *Zishi*; Credit: Bart van Overbeeke, 2016. (b) The conductive embroidered pattern on which the hard electronics are attached with magnets; Credit: Wang Qi 2016. (c) System architecture of *Zishi*; Credit: Wang Qi 2016.

Zishi: embedding vibrotactile notifications in wearables for rehabilitation

Zishi (Figure 1), which means 'posture' in Chinese, is a smart garment designed to support two use cases: (a) posture correction during physical rehabilitation training (Wang 2016) or (b) self-tracking and correction in everyday life (Du et al. 2017).

Zishi consists of four parts (see Figure 1(c)):

1. A garment integrating wearable smart textiles and connection points.
2. A flexible central node that embeds sensors, data processing components and a communication module.
3. A modular soft electronic package with a sensor and a vibration motor.
4. An Android^{TM} application for visual and audio feedback.

In *Zishi*, vibrotactile feedback serves to indicate that the user's posture exceeds a personalised setting. The vibration motors are placed on the shoulder and the chest to help the user associate the feedback with the direction of the deviation from the upright position. The main challenge regarding the aesthetic integration of vibrotactile output in the garment concerns the integration of hard electronics into soft textiles without compromising appearance and comfort. During the iterative design a variety of solutions have been explored (Figure 2) and the embroidered circuits were themselves designed with an eye on their appearance.

Zishi has been evaluated in laboratory experiments with patients and therapists regarding different aspects of user acceptance in the context of rehabilitation training for the shoulder (Wang, De Baets, et al. 2017) and arm-hand training after stroke (Wang et al. 2018). It has also been field-tested as a self-tracking device for posture correction of office workers, who wore it through the day while going about their daily tasks (Du et al. 2017). These studies evaluated the system holistically rather than the vibrotactile actuation as such; they provide extensive evidence for the acceptance of the *Zishi* system by patients (25 in total), healthy participants (8) and therapists

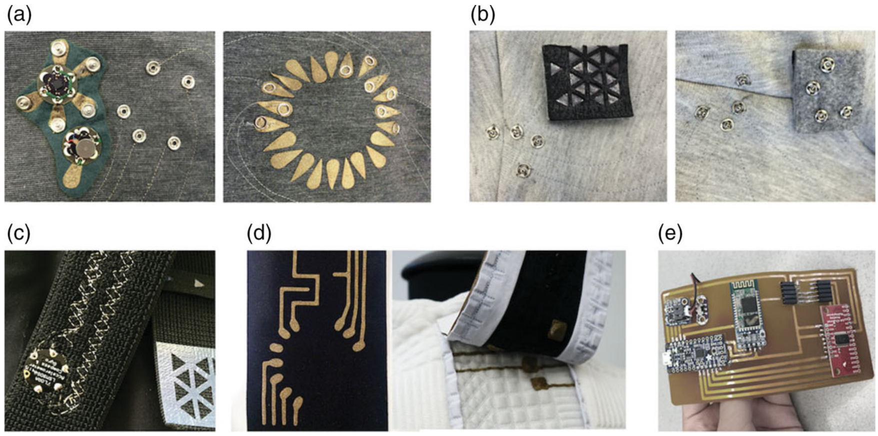

Figure 2. Explorations on how to connect detachable hard electronics to the soft garment: (a) Polyester conductive thread and fabric with pronged cap; (b) Stainless steel conductive thread with snaps embedded in the garment as connection with the sensor unit; (c) Coated conductive thread sewed and soldered with the sensor; (d) Conductive fabric pattern for connecting the electronic modules and tiny magnet under the square fabric as connection point between the sensor package and garment; (e) Flexible PCB. Credit: Wang Qi, 2018.

(8 in total), appreciation of its usability, a positive assessment of the credibility of the device as a tool for rehabilitation and its efficacy for posture correction. Across these studies patients and therapists gave positive comments regarding the wearability of *Zishi*.

Vibe-ing, self-control interface

Whereas *Zishi* considered aesthetics in terms of the garment appearance, vibrotactile feedback also enables new interactive experiences, which can be considered for their aesthetic qualities. This design space was explored with *Vibe-ing* an interactive cardigan for self-care (Figure 3) that invites the body to feel, move, and heal through vibration therapy. By stimulating selected acupressure points on the body, e.g. touching a sore lower back, *Vibe-ing* was designed to encourage subtle exploration and connection with oneself.

Vibe-ing was assembled from digitally designed, pre-shaped pieces of knitted textile produced using a full-fashioned knitting machine (Bhomer, Tomico, and Wensveen 2016). The knitting and felting technique used resulted in a soft and bulky surface, designed to invite the wearer to stroke and touch the fabric and the body, in order to provide comfort (Figure 3). The textile construction contains pockets in which circuit boards with sensors (touch sensors) and actuators (vibration motors) are placed (Figure 4, left). Specially developed casings help transfer the vibration to the skin. A vibration starts in the pocket touched by the person wearing the garment. The wearer can press their hand on any of these pockets, to direct and control the intensity and duration of the vibration patterns delivered by the system.

Figure 3. General look of the *Vibe-ing* garment. Photography: Hanneke Wetzer & Bas Berends, Hair & Make-up: Jaimy Bontenbal; Model: Jos van der Weele, 2013.

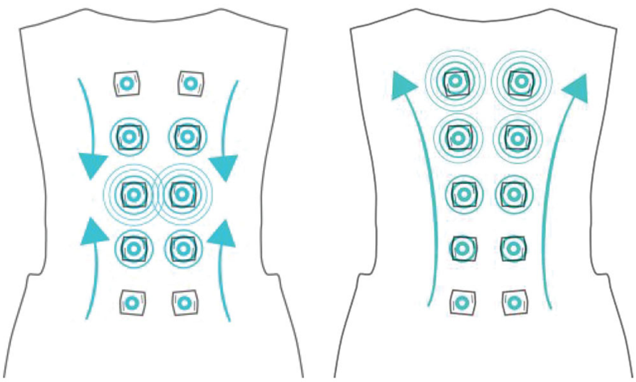

Figure 4. Activation patterns for *Vibe-ing*: Left: The bidirectional pattern converging to the point where the user touches the vest. Right: Simple upward vibration pattern. Credit: Martijn ten Bhomer 2016.

The *Vibe-ing* prototype was user-tested with 9 women in their menopause. The test concerned the user experience aspects relating to the vibration feedback rather than the efficacy of the device as a therapy aid. Participants were asked to put on the cardigan and to freely explore how the touch interaction feels. They could then experience two distinct vibration patterns, where the successive activation of vibromotors produces the sensation of a rippling movement on the skin moving either upwards from the point of contact, or bi-directionally converging towards the point of contact (Figure 4). Participants were interviewed regarding their experience and were invited to write a love and a break-up letter to the device as a playful way to invite comments reflecting their personal experience and attitude towards it. From the letters we learnt that most participants preferred the upward vibrotactile pattern over the bi-directional one; it was often mentioned that the bi-directional vibrotactile pattern felt random and out-of-control. In the

Figure 5. Left: Electronic boards with vibration motors are inserted in casing, and consequently integrated in the garment. Right: User pressing the pocket with casing onto the body to direct and control the vibration. Credit: Martijn ten Bhomer, 2015..

interview, participants also commented how the vibrations were sometimes not felt as the garment was not tight enough: '*I only feel the vibrations on my back when I sit or stand against the back of the chair or the wall.*'

Regarding the design process, it became clear that providing tools for easily modifying and experiencing vibration patterns is key to support fast iterations. These are necessary as it is difficult to imagine and discuss complex haptic sensations without experiencing them. Using generic tools such as the Arduino designers are confronted with complex low level technical issues. Accordingly, a programmatic interface was developed that allows setting different vibration patterns by adjusting 19 parameters, thus raising the level of abstraction at which designers operate to enable efficient iteration (Figure 5).

Tunnen: simulating a caring touch

Tunnen integrates haptic feedback in a garment in an attempt to emulate an important element of therapist-patient interaction, where a therapist guides the patient through gentle nudges that communicate direction of movement, and perhaps as important, have an emotional and social significance to encourage and support the patient.

Four vibration motors installed at the shoulder area communicate the intended movement direction, e.g., a directional nudge at the back is delivered to suggest bending forward. To simulate a caring touch/pat on the shoulder four solenoids were placed close to either scapula thoracic or lumbar nerves. The final design resembles a form-fitting sport bra (Figure 6). To ensure comfort, a silicon casing is placed between the actuator and the human skin.

The design was constructed iteratively with the involvement of therapists and patients who could provide a first-person perspective on how such physical nudges are used and experienced in the context of traditional therapy sessions and how these could be simulated by technical means. In a co-

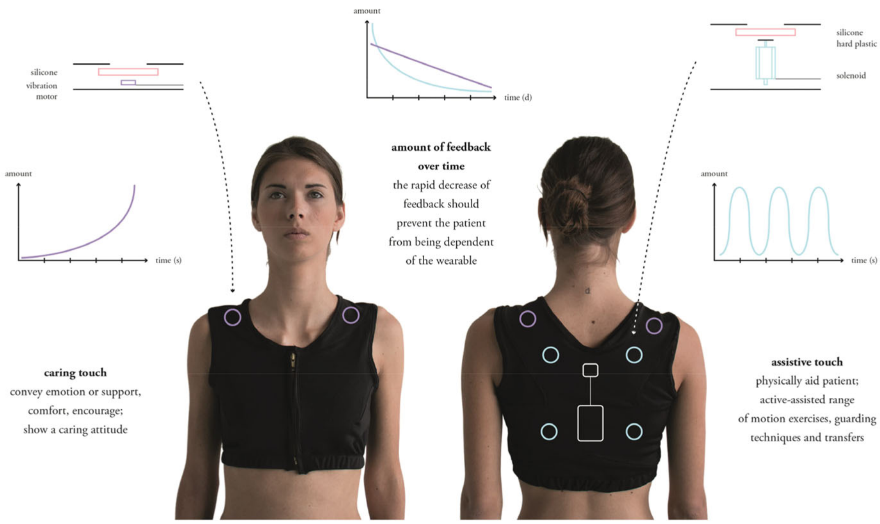

Figure 6. *Tunnen*: Simulating the therapist's caring touch with vibration motors and solenoids. Credit: Nita Virtala, 2016.

reflection session six physiotherapy students evaluated the two forms of haptic feedback by trying out the device. Participants described the directional nudge with terms such as '*recognisable*' '*comforting*' and '*warm*' and agreed that it could 'stimulate slow correction'. The encouragment pat was less successful and one patient described it as '*superficial*' and another as '*poking*', comparing it to '*a glucose meter*'. A therapist was concerned with the time patients need to notice a nudge delivered in this way, commenting that '*you want to make sure that the patient has time to recognise the type of feedback*'. Currently the affective aspect of haptic feedback (pressure or vibrations) is not yet understood sufficiently. Transcending a soft stroking sensation which was considered with *Tunnen*, future design explorations could unpack the emotional signification of different feedback forms such as pressing, tapping, tickling, stretching and brushing in order to guide the design of expressive haptic actuation in wearables.

Squamae: peripheral movement-based feedback

Whereas vibromotors used in the previous prototypes display binary information or at best can help users discriminate between 3 and 4 levels of a variable (e.g. by varying the length of vibration as in (Benini et al. 2011), soft robotics and shape changing devices can display continuous output ranges with higher resolution and more varied and aesthetic dynamics.

Squamae is a design exploration into using movement to display feedback at the periphery of a user's attention thus allowing users to focus on different tasks, while maintaining an awareness of their own posture. *Squamae* is

Figure 7. *Squamae* movement-based posture feedback display. Left: An array of actuated flaps can be animated in different ways to provide directional feedback to the user. Right: Successive animation of rows or columns creates a wave pattern to give feedback on the shoulder posture. Credit: Luca Giacollini, 2016.

a haptic and visual grid display made out of individually programmable ‘physical pixels’ that can change their actuation state, and therefore create motion choreographies as explained below. It can be worn on the lower arm, within the periphery of one’s vision. Technically, *Squamae* consists in 16 linear actuators that are covered with 3D printed flaps (Figure 7). Each flap rotates outwards from the arm. An Arduino board handles both the state of the actuators (on/off) and the communication with the input system, which is the sensing garment *Zishi* discussed above. Rapid choreographies of the grid can support descriptive feedback (i.e. the activation corresponds to the sensed body part or movement) and prescriptive feedback (i.e. showing the direction towards which the user should direct his/her upper body).

The coupling of motion and actuation in *Squamae* is key to rendering the output meaningful and aesthetically pleasing. *Squamae* combines the different dimensions of coupling of user motion and feedback identified in the Frogger framework (Wensveen, Djajadiningrat, and Overbeeke 2004): time, location, direction, dynamics, modality and expression. Iterative exploration of different coupling principles focussed on how users experience and interpret the resulting choreographies. The naturalness of feedback seems to be influenced by the match between the direction of animation of the flaps with the movement of each one, how well the timing of the feedback matches the direction and timing of user gestures, etc. Eventually the designer settled with two actuation patterns: a ‘wave’ from the back to the front row when the user is slouching. or a ‘wave’ from one side to another according to the relative balance of the shoulders (Figure 7(b)). In both scenarios, the movement displayed is a mirrored representation of one’s posture displacement.

Squamae is still but a proof of concept which has not been user tested for its efficacy as a feedback device. From a technical perspective, in order for such a technology to be deployed effectively for the purposes of motor learning two major developments are needed: Firstly, the device should be made smaller by using purpose-made solenoids suitable for wearing, e.g., using embroidered copper thread in spirals and, secondly, the power consumption of the actuator grids needs to be improved for allowing portability.

PosturePillar: on skin shape changing feedback

PosturePillar is a wearable inflatable silicon chamber that uses air pressure to give haptic feedback on the user's lumbar posture (Figure 8). *PosturePillar* is made of soft bendable silicone to fit the body shape; haptic feedback can range from very subtle to very intense and can be sustained for long durations if necessary. It is worn on the lower back with a cavity facing towards the user's body. This cavity has one wall (membrane) thinner, so when inflating the cavity's structure helps direct the inflation. A mini pump controlled by an Arduino is used to pump the silicon balloon. Unlike vibration motors having a binary state (on/off), *PosturePillar* features analogue feedback which supports richness and expressivity of the output. On the other hand, inflation

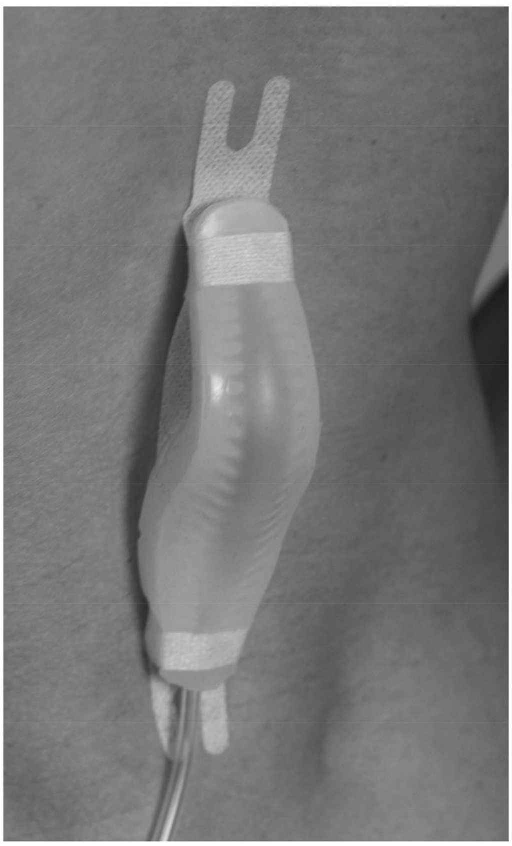

Figure 8. *PosturePillar*: an inflatable silicon chamber adhered to the back of the user that applies a gentle pressure on the user's body when they should remember to adjust their posture. Credit: Mantas Palaima, 2015.

takes longer than vibration, which makes it less suitable in cases where a quick response is expected from the user and the interaction is faster paced.

The design of *PosturePillar* highlighted several challenges in designing and integrating pneumatically actuated soft composite materials as well as for fitting these devices to the body: apart from being slow, air pumps can be noisy and bulky if they are to produce sufficiently perceptible deformations; providing precise feedback on the body requires an expert to adhere the device on the skin at the appropriate location and the adhesive can be uncomfortable or even irritating for the skin. Finally, whereas encouraging users to have a good lumbar posture is rather simple, more complex forms of motor learning may require more precise positioning of the actuators and synchronising the actuation in response to user movements. These topics are explored further with the design of *Flow* discussed below.

Flow: towards communicating directional cues through inflatables

Flow delivers directional cues as a push against the body, coupling the direction of actuation and the direction of intended movement. Wrist and arm movements are separated into fundamental movements of the wrist (adduction, flexion and extension) and forearm (supination and pronation) as reference for the six actuation points (Figure 9(b)). The complex motion sequence that the user has to learn (such as, defence and attack in fencing skills) are separated into sequences, conveying to the user the desired direction as the pressure points push against the body.

The result (Figure 10) is a wearable artefact made entirely of silicone (Ecoflex® 00-30 hardness) which is cast in a mould with PVA inserts, both 3D printed. The inserts create the paths for actuating six points corresponding to the fundamental joint movements of the wrist and the forearm. The airways of this wearable are inflated through air pumps controlled by a micro controller.

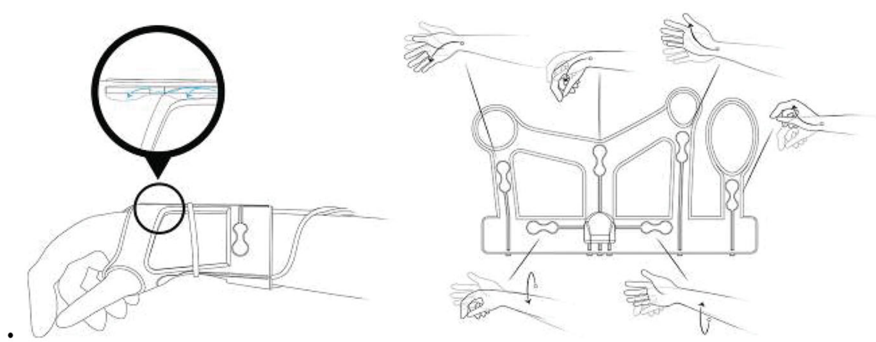

Figure 9. Left: Schematic of the air flowing to actuate point that cues flexion of the wrist; Right: The six actuation points and the respective fundamental joint movements they cue. Credit: Bruna Goveia da Rocha, 2015.

Figure 10. *Flow* on the body of a fencer. Credit: Bart van Overbeeke, 2015.

Actuation in wearables often relies on external (hard) mechanisms placed on the body (Du et al. 2018), restraining wearability and increasing the complexity of fabrication of the wearable. In this design, the wearable operates as a material extension of the actuators as the air pumps responsible for the pressure feature to be relocated from the area of actuation. The wearable can thus be technically and materially sophisticated yet remain lightweight. A key design consideration pertains to the dynamics of actuation; the right timing and intensity can prompt a playful experience that allows the user to positively engage with the training.

Discussion

Current approaches for providing feedback on interactive clothing that are based on vibrotactile notifications are limiting as they provide relatively coarse movement feedback and are limited from an aesthetic perspective (Yamazoe and Yonezawa 2017). We presented six design explorations that aim to address these limitations and expand on the haptic and shape changing feedback possibilities that can be applied to support motor skill learning.

With the design of *Zishi* we explored the aesthetic and functional integration of vibromotors to a wearable sensing garment to support various posture correction. In *Vibe-ing,* our focus shifted onto the aesthetic aspects of vibrotactile actuation and the experience that emerges from coupling actuation to user touch input. *Tunnen* explored the complexities of effectively conveying affect. *PosturePillar* explored dynamic shape change as a way to convey nudges to correct posture. *Squamae* and *Flow* explored synchronising and aligning actuation to movement. The devices described in this paper are all concept prototypes, constructed to create 'experientiable' exemplars of the intended interaction. Only *Zishi* and *Vibe-ing* can be considered as fully integrated systems, that can support rehabilitation-training, and these relied on the most conventional of haptic output modalities, vibrotactile output. This observation is quite representative of the current state of the art. Current attempts to support motor learning with vibrotactile feedback are not yet integrated in complete systems that can support full training scenarios and applications.

From the design concepts presented here only *Zishi*, *Vibe-ing* and *Tunnen* have been tested with users, and in the latter two cases the testing was limited in scale and provided qualitative evidence only. Further research should examine the integration of feedback modalities that actuation allows with particular emphasis on the aesthetics and wearability aspects that are often neglected when studying the efficacy of training or rehabilitation systems.

Integrating actuation in smart clothing is promising as it enables to extend motor learning for prevention and rehabilitation into everyday life. Considering examples such as *Zishi* and *Vibe-ing* it is clear that some distance needs to be travelled before such technologies appear as commercial products. Bryson (2009) comments on the inherent tension between the need to demonstrate the efficacy of the technology in rigorous trials and addressing aesthetic concerns of clothing. He argues that the former leads to long development trajectories for the healthcare sector which are not compatible with the 'here today-gone tomorrow' nature of the fashion world.

In the design cases presented we have explored alternative output modalities including movement and shape-change. The prototypes created illustrated some of the challenges involved in creating practical solutions for motor learning:

1. Electromechanical parts, especially solenoids produce a lot of noise and need to be replaced by other technologies that are silent and easy to integrate in textiles
2. Improvements are needed regarding the precision and speed of control for actuators, their miniaturisation and integration into clothing
3. Aligning spatial and temporal aspects of the actuation to the sensed human movement in real time is required.

From a design perspective, we note how methodological knowledge is lacking concerning the aesthetics of actuation in wearables. Relevant inspiration can be drawn from ecological perception inspired approaches like the Frogger framework or practical approaches like the somaesthetics appreciation design (Höök et al. 2016).

Squamae, *PosturePillar* and *Flow* involved coarse shape-change feedback; an increase in shape change resolution could provide new opportunities to designers. The concept of shape change resolution (Kim, Coutrix, and Roudaut 2018) refers to the number of shape features (a maximum of 10 features are proposed) which can be dynamically modified during interaction, e.g. granularity, porosity, zero-crossing, amplitude, strength, speed. Of these, strength and speed are relevant in the domain of motor learning as they can provide guidance to control user motions. An important feature not adequately addressed by (Kim, Coutrix, and Roudaut 2018) concerns the way that actuators are combined and behave. On the one end, a display can be 'pixelated' meaning that the configuration of actuators can be compared to a matrix of pixels which are actuated individually to produce arbitrary shapes. On the other end, complex shapes are known a priori and shape change may transition between pre-defined states, e.g. in Origami like structures. In smart clothing a combination of the two approaches may be conducive towards achieving the fine grain control of analogue shape change and the flexibility of the 'pixelised' solutions. The *Flow* prototype relies on binary transitions of its pneumatic actuators to provide complex movement feedback by aligning actuators carefully to different parts of the arm and wrist.

The solutions discussed are limited by the extant actuation technologies that we integrate as off the shelf components into wearables. Improving upon the aesthetics and the comfort of the devices could benefit from developing new materials for supporting wearable actuation. For example, *Shapetex* illustrated the use of laminate thermal expansion to actuate textiles (Du et al. 2018). *Shapetex*, just like the designs discussed in this article, apply small forces as haptic/movement-based notifications or guidance, and are not intended to physically support the user in moving as an exoskeleton would. Clearly, the development of soft robotics and structures that will be able to apply larger forces, can be expected to blur such distinctions in the future and to facilitate the integration of actuation in wearables.

The prototypes presented required considerable effort and manual work to be realised and the designers were often confronted with the need for prototyping tools that will facilitate iterative design explorations. For example, in *Vibe-ing* (Bhomer, Tomico, and Wensveen 2016), the iterative design of actuation patterns necessitated the development of a platform for rapid and iterative prototyping of vibromotor activation patterns. Similarly, *Shapetex* (Du et al. 2018) discussed above, was introduced with a simulation tool, to allow predicting the deformation speed and extent of the material in different sizes and shapes. Such developments help speed up iteration and improve the predictability of outcomes but do not go far enough in providing integrated support for modelling human motion and mapping feedback. More generally, we need to develop digital techniques for prototyping interactive clothing, allowing precision and reproducability whose combination is key for supporting incremental modifications/improvements of a design as well as tailoring of the prototypes created to different user bodies. Such techniques, will cross traditional boundaries between high tech components (e.g. the electronic parts), and low-tech prototyping (e.g. sewing, embroidery), as was the case with *Zishi* and the other examples presented here, to allow fast and accurate reproduction and tailoring of smart textile solutions that embed actuators.

Little is known yet regarding the effectiveness of the forms of wearable feedback that we discussed for motor skill learning. A recent systematic literature survey on applications of vibrotactile feedback in sports and motor learning, found mixed evidence regarding its effectiveness (Breda et al. 2017). However, most uses of this technique concern the intensity of training rather than the quality of the motion as such. Two related studies (Lieberman and Breazeal 2007) (Bark et al. 2015) argue that adding vibrotactile feedback (delivered on the body with a vibrotactile vest) to visual feedback helps improves motor learning, and can accelerate the learning of arm movements with single and multiple degrees of freedom. It is up to future research to establish the effectiveness of the other forms of haptic feedback discussed in this paper. Where the intended use is as part of everyday life (as opposed to rehabilitation or sport training sessions in dedicated environments such as a gym or a clinic), evaluation needs to extend beyond effectiveness to include wearability/comfort and social acceptance of the clothing.

Conclusions

We have described six design explorations into wearable actuators for motor skill learning drawing attention to emotional, aesthetic, and comfort aspects. Aesthetics in this case concerned partly the total appearance of the garment, but also the very qualities and expressivity of the feedback and the user experience for participants in user tests.

Amongst the actuation approaches considered, vibrotactile feedback is the most mature, for which evidence already exists regarding its effectiveness in supporting motor learning. Our designs illustrated ways of aesthetically integrating vibrotactile actuation into smart garments. We also examined how shape change, either through electromechanical actuation or pneumatics, can support aesthetic and intuitive forms of feedback and affective communication. We identified several technical challenges that need to be overcome to enable the wider application of these feedback modalities in the future including the portability of high-pressure pneumatic actuation, noise reduction, miniaturisation.

Currently wearable actuation, especially in clothing remains a novelty that is still not fully understood from a design or user experience perspective and is not sufficiently supported by methods, tools and guidelines. Future research challenges concern: (a) enabling fast prototyping through specialised hardware and software platforms that can make technical details transparent to designers, (b) taking design concepts all the way to implementation and clinical testing, to demonstrating the impact and added value of actuation for motor learning, (c) developing design methodology for enhancing the effectiveness and aesthetic quality of actuated feedback.

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