Easy Undressing with Soft Robotics

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Abstract. Dexterity impairments affect many people worldwide, limiting their ability to easily perform daily tasks and to be independent. Difficulty getting dressed and undressed is commonly reported. Some research has been performed on robot-assisted dressing, where an external device helps the user put on and take off clothes. However, no wearable robotic technology or robotic assistive clothing has yet been proposed that actively helps the user dress. In this article, we introduce the concept of Smart Adaptive Clothing, which uses Soft Robotic technology to assist the user in dressing and undressing. We discuss how Soft Robotic technologies can be applied to Smart Adaptive Clothing and present a proof of concept study of a Pneumatic Smart Adaptive Belt. The belt weighs only 68 g, can expand by up to 14% in less than 6 s, and is demonstrated aiding undressing on a mannequin, achieving an extremely low undressing time of 1.7 s.

Keywords: Healthcare, Adaptive Clothing, Soft Robotics, Wearable Robotics

1 Introduction

Limitations in dexterity affect a large number of older adults and people with a disability: in the UK, 21% of men and 30% of women aged 65 and over need help with at least one Activity of Daily Living (ADL) [1], and 27% of people with a disability report dexterity impairments [2]. During focus groups discussing wearable robotic technology with older adults and people with a disability [3], one commonly reported requirement was that clothing should be easy to put on and take off (Fig. 1). For example, people who have had strokes often experience difficulty dressing: one study found 36% of patients could not dress independently 2 years after a stroke [4]. In addition to being challenging, dressing and undressing can be a source of pain, such as in patients who suffer from rheumatoid arthritis [5]. For people living with dexterity impairments, shortening the time taken to undress can be especially important given the increased complexity of other urgent tasks, such as going to the toilet.

Figure 1. One of several illustrations drawn to capture views expressed during focus groups with older adults and people with a disability. For assistive technology, ease of putting on and taking off was a regularly reported necessity. Illustrations by local artist Bethan Mure http://www.bmurecreative.co.uk/

Usually, independence when performing personal activities can be improved through occupational therapy [6]. However, independence may also be improved through Soft Robotic technology: for example, the well-known McKibben pneumatic artificial muscle was originally invented in the late 1950s by Joseph L. McKibben for his daughter Karen McKibben, who was paralyzed with polio [7, 8]. Many robotic products have since been proposed to assist the ageing population, however these are often not well matched to that population's desire for accessible and easy-to-use technology [9].

Some research has been conducted in terms of robotic assistance in dressing and undressing. Upper body dressing has been demonstrated using a dual-arm humanoid robot [10], and lower body dressing has been performed using a life-sized humanoid robot [11]. Sensing during dressing has also been studied [12].

Wearable robotic assistive devices have also garnered considerable interest in recent years. McKibben pneumatic artificial muscles have been included in orthotics for ankle flexion [13], knee assistance [14] and even whole lower body assistance to augment normal muscle function in healthy users [15]. Flat pneumatic artificial muscles have been included in a knee orthotic [16], and shape-memory alloy wire has been proposed as an actuation technology to assist with ankle and knee movement [17]. A knee extension orthotic has also been described using PVC gel actuators [18].

A common solution is to use DC motors, which are either mounted on an immobile base [19], mobile trolley [20], or in a bulky backpack. Rather than deliver power directly to the joints as in an exoskeleton, power can be transmitted using Bowden cables, to achieve post-stroke shoulder rehabilitation [21], ankle extension [22], and hip extension [23]. Another design uses DC motor driven drums, which spool fabric ribbons to provide power for hip extension [24].

In all of these examples, the wearable robotic assistive device is designed to exert forces upon the body, usually to provide additional power to joints and limbs. Some research has been done on making adaptive fabrics, which can controllably change either their shape [25] or their stiffness [26], however we were unable to find any examples of soft robotic clothing that adjusted its fit to promote ease of dressing in those with limited dexterity. Although adaptive clothing has been explored in fiction (Marty McFly's shoes in Back to the Future Part II) and fashion (Nike MAG), it has yet to garner serious academic or healthcare attention. This is especially noteworthy because easy dressing and undressing was so often described as an essential capability for mechanically assistive clothing in focus groups. Inevitably, some users will have sufficient dexterity that non-robotic solutions (such as elasticated clothing with magnetic or hook-and-loop mechanisms) are sufficient. However, for users with severe dexterity impairments even these may be challenging and painful to use. These users require clothing that can easily be put on and taken off without direct physical interaction.

To address this need, we introduce the concept of Smart Adaptive Clothing, able to independently adjust its fit to help with dressing and undressing. We discuss some ideal qualities of the clothing and describe how the desired behaviors might be achieved. In each case, we refer to existing Soft Robotic technology that could be exploited to achieve the desired behavior. Finally, we present a proof of concept study and demonstrate an assistive belt powered by expanding pneumatic artificial muscles, capable of rapidly increasing its diameter, promoting simple, fast and comfortable dressing and undressing.

2 Easy On, Easy Off

Fig. 2 shows the fundamental Smart Adaptive Clothing concept. The clothing should be capable of switching between two states – a loose fitting state and a tight-fitting state. During dressing, the user can more easily put on the loose-fitting clothing (a), before initiating its transition from a loose-fitting (b) to a tight-fitting (c) state. During undressing, transitioning the clothing to its loose-fitting state should allow for rapid undressing.

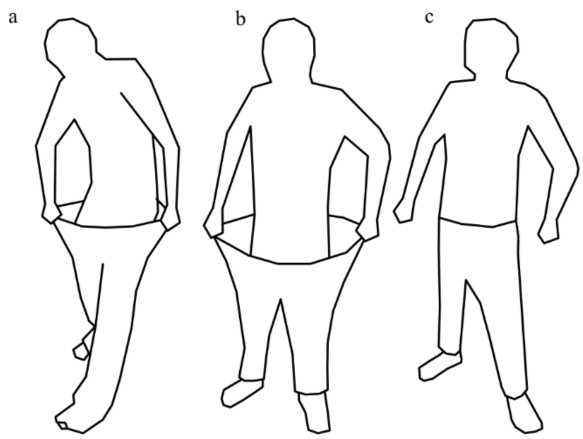

Figure 2. Concept drawings for Smart Adaptive Clothing. (a) Putting on adaptive clothing while in a loose-fitting state. (b) Ready to tighten adaptive clothing. (c) Smart Adaptive Clothing tightens to a comfortable diameter.

To achieve this behavior, the clothing requires one or more circular elements that are able to increase or decrease their diameter, which surround parts of the body, such as waist, legs or arms. A greater change in diameter will be more beneficial up to a point, beyond which the loose-fitting diameter might be too large, and the clothing might become unwieldy and too hard to use. The exact change in diameter required will vary depending upon the user's preference.

The energy cost of changing fit is also an important performance metric; for clothing with on-board power, it will determine time-between-charges for the clothing.

We propose two separate behaviors that could be exploited to achieve Smart Adaptive Clothing: variable stiffness structures and artificial muscles. In the case of variable stiffness structures, the compliance of the clothing can be controlled. When the clothing is in a compliant state, the user will easily be able to stretch it to a large diameter. Once the user is ready, transitioning to the stiff state will cause the clothing to tightly fit the body. In the case of artificial muscles, the clothing will contain one or more actuators that can extend or shorten, directly controlling the fit of the clothing based on the user's requirements.

3 Variable Stiffness Clothing

3.1 Active Stiffening

We will first consider technology that becomes stiffer upon activation. Variable stiffness technology may be less attractive to users compared with actuated clothing, since no mechanical work is done by the technology and the user must adjust the fit of their clothing themselves; however, this can mean that the energy costs associated with state change are lower. With active stiffening clothing, the technology must be activated for the clothing to transition to a tight-fitting state.

In magnetorheological or electrorheological fluids, an applied magnetic or electric field can increase stiffness [27]. Similarly, electroadhesive structures can adhere to surfaces [28] or between layers [29] allowing an almost forty-fold increase in stiffness. However, the magnetic or electric field would need to be maintained while the clothing is in its stiff (tight-fitting) state, implying a continuous power requirement while the clothing is worn.

Granular jamming, whereby applied negative pressure results in a granular media (such as coffee grains) "locking" together [30] could provide a similar effect, and it should be possible to maintain the negative pressure at no power cost by closing a valve. However, clothing filled with granular media (or magneto- or electrorheological fluids) may not be comfortable to the user or aesthetically pleasing.

3.2 Active Softening

Active softening variable stiffness materials will become less stiff when activated, allowing the user to easily dress and undress. These may be advantageous over active stiffening materials since the material only needs to be active during short dressing and undressing periods.

Many materials become softer when heated, however some materials can exhibit a considerable and reversible stiffness change by being heated above their glass-transition temperature. At this temperature, they transition from a hard, brittle glass state to a soft, rubbery amorphous state. This process can be achieved by joule heating of embedded electrically conductive materials [31]. Glass transition materials could be quite suitable for embedding within Smart Adaptive Clothing, although the requirement for thermal activation can result in longer heating times compared with electroactive materials, making them less suitable for rapid dressing and undressing.

4 Mechanically Active Clothing

Current artificial muscle technologies also show great potential as the active materials in Smart Adaptive Clothing. Most artificial muscles exhibit tensile shortening and so could be embedded in the waistline of a lower body garment to form a ring that would tighten upon the muscle's activation.

4.1 Active Tightening

Coiled polymer actuators are a recent thermoactive artificial muscle technology, whereby twisted and coiled polymer fibers reversibly untwist when heating, resulting in large strokes and forces [32]. Homochirally wound coils (where the direction of coiling matches the direction of twisting) can contract by up to 49% when heated. Coiled polymers can be made from synthetic fibres such as nylon and therefore are well suited for inclusion in clothing – they could be easily integrated into the waistband of a lower body garment and heated to tighten the garment's fit. Shape-memory alloys actuators behave similarly, shortening when heated, and could be integrated in the same way [33]. The fibers may need shielding from the user's skin to prevent discomfort or burns if the temperature of operation is high; in [32] they were heated above 100 °C, which would necessitate thick insulation. However, such high temperatures may not be necessary if lower contraction ratios are permissible.

As with active stiffening variable stiffness technology, both solutions would need the technology to be active all the while the garment was worn. Given that coiled polymers and shape-memory alloys are thermally driven, this could imply high energy costs and discomfort associated with long term heating.

Various fluidic artificial muscles, such as McKibben, pleated [34], Pouch motors [35], Peano muscles [36], vacuum-actuated muscle-inspired pneumatic structures (VAMPs) [37] and fluid-driven origami-inspired artificial muscles (FOAMs) [38] can contract when a positive or negative pressure is applied and could be included around the waist to contract and tighten the fit when activated. Those driven by positive pressure (McKibben, Pouch motor and Peano muscles) have the added advantage of fattening laterally when activating, which would further tighten the fit. With fluidic systems, valves can be used to close off the tightening structure while the garment is worn, resulting in zero energy costs while wearing the clothing.

4.2 Active Loosening

Active loosening technology seems best suited for the Smart Adaptive Clothing. Clothing containing these materials would be tight while passive, and the actuators only need be activated during dressing and undressing, keeping energy costs low. Furthermore, in contrast with actively softening variable stiffness technology, here the actuators do the work required to loosen the garment, maximizing the convenience to the user, who may only have full use of one arm, as is common in the case of people who have had strokes.

Heterochirally coiled polymer muscles, in which the chiralities of coils and twisted fibers are opposed, expand by up to 67% during heating [32]. These could be readily integrated into Smart Adaptive Clothing. Two-way shape-memory alloy structures can also be programmed such that they elongate by heating and contract upon cooling. For example, shape-memory alloy springs can reversibly expand by over 90% of their initial length when heated to 65 °C [39].

Various bellows-like soft actuators expand longitudinally and contract laterally when they are inflated by air, so could be used for as loosening structures around the waistline [40]. In all fluidic actuators, replacing the working gas with a liquid will reduce the volume required to achieve a desired output force (assuming incompressibility), and can also allow for sensing of expansion and contraction [41]. Similar to bellows actuators, fiber wound inverse pneumatic artificial muscles (IPAMs) have been shown to exhibit up to 300% expansion when filled with high pressure fluid [42]. IPAMs are especially suited for Smart Adaptive Clothing because of their high strain, small cross-sectional area, and fast response time.

5 Case Study: Pneumatic Smart Adaptive Belt

In this section, we present a Pneumatic Smart Adaptive Belt powered by inverse pneumatic artificial muscle technology. As in the rest of the article, the desire is to design a device that can transition between a tight-fitting and loose-fitting state, speeding up and simplifying dressing and undressing.

We based the design of the Smart Adaptive Belt upon the inverse pneumatic artificial muscle. To construct the belt, we began with a length of 10 mm diameter, 1 mm wall thickness silicone tubing (T10X1ST60, Polymax Ltd, UK). Using this tubing alone, application of pressurized air induces axial lengthening but also radial expansion, and the tubing is liable to burst before large axial lengthening has occurred. To prevent radial expansion and raise failure pressure, the tubing was wrapped with 0.08 mm diameter braided fishing line (6LB SeaKnight Classic Line Braid x 4, SeaKnight, China). During inflation, as the belt lengthens axially, the gap between adjacent bindings increases; to ensure radial expansion was limited even at high pressures, we pre-stretched the silicone tubing by 40% prior to binding. The tubing was wrapped twice, once in each direction, and the bindings were held in place using a thin silicone adhesive coating (Sil-Poxy, Smooth-On, US). The bound tubing was cut to length and connected to a pneumatic T-connector using hose clamps to form the Smart Adaptive Belt. The belt mass was 68 g.

Fig. 3 shows results from characterization experiments with the belt. The pressure was recorded using a pressure sensor (HSCSAAD060PDAA5, Honeywell, US), and the average diameter (based on maximum and minimum diameter) was determined from images using MATLAB image processing commands. Pressure was applied using a small 12 V vacuum pump (ROB-10398, SparkFun, US). Repeatable 13% circumferential expansion was achieved at an applied pressure of ~180 kPa. In imperial units, the belt circumference increased from 33.39 to 37.84 inches, an increase of roughly two standard clothes sizes.

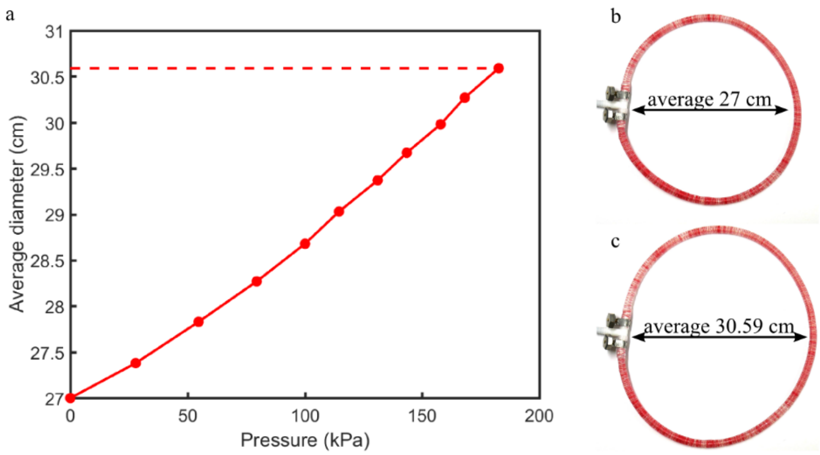

Figure 3. Pressure induced expansion of the Pneumatic Smart Adaptive Belt. (a) Average diameter variation with applied pressure. (b) The belt at rest, with an average diameter of 27 cm. (c) 13% expansion was achieved by application of ~180 kPa.

Fig. 4 shows results from experiments to determine the expansion and relaxation speeds of the Pneumatic Smart Adaptive Belt. In these experiments pressure was not recorded, and diameter was determined from captured video using MATLAB. 14% expansion was achieved after 5.5 seconds of inflation (Fig. 4a), while in relaxation experiments, the belt returned to 1% greater than at-rest diameter after 0.37 seconds and relaxed fully after 2.7 seconds.

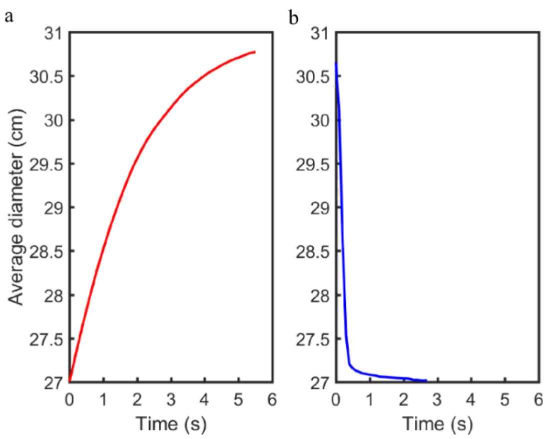

Figure 4. Results from expansion (a) and relaxation (b) experiments with the Pneumatic Smart Adaptive Belt. 14% expansion was achieved after 5.5 seconds of inflation. Relaxation to 1% greater than at-rest diameter was achieved after 0.37 seconds, and full relaxation to at-rest diameter after 2.7 seconds.

Finally, we performed experiments using the Pneumatic Smart Adaptive Belt worn by a wooden mannequin (Fig. 5). The fit of belt was tight enough to secure a pair of jogging bottoms to the mannequin (the resting diameter of the belt will determine its tightness of fit). Upon application of pressure, the Smart Adaptive Belt's diameter increased, and the jogging bottoms fell to the floor. The undressing time (from initiation of inflation to the garment falling to the floor) was 1.7 seconds, which should be sufficient for even urgent tasks such as going to the toilet.

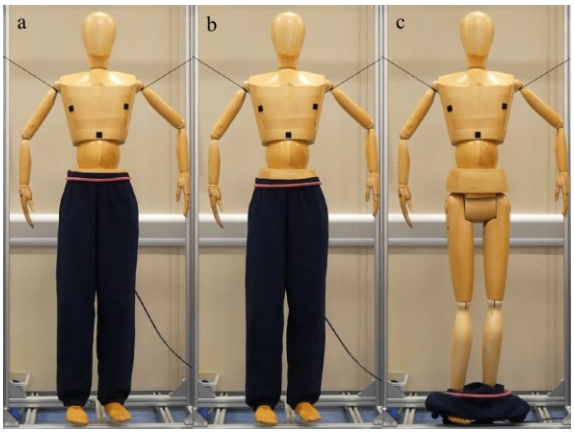

Figure 5. Snapshots from video taken during experiments with the Pneumatic Smart Adaptive Belt on a wooden mannequin.

Being an active-loosening prototype, the Smart Adaptive Belt has the advantage of only consuming energy when being put on or taken off. It has a high expansion coefficient, allowing a large difference in tightness between its tight- and loose-fitting states, and it can change its fit rapidly. Disadvantages include the fact that it will assume a circular cross section when inflated, making it less like a belt, which may put off users. Additionally, inflating the belt with a pump or air supply produces an audible (though not loud) noise, which may be undesirable for some users.

Future work will involve improving the maximum expansion of the belt and minimizing the air supply and control systems so that they can be mounted on-board. We are currently developing a portable air supply for the belt driven by a 12g CO_2 cartridge and valve which has a combined weight of less than 100 g. Because the compressed air is delivered by the CO_2 cartridge, the electrical power requirements are very low; the 3 V valve (S070C-RBG-32, SMC, Japan) consumes 0.35 W (~117 mA) while open, so a tiny 2.65g 110 mAh lithium polymer battery can provide roughly one hour's worth of valve operation, or ~650 inflations (14% expansion was achieved after 5.5 seconds of inflation). We have not yet tested how many times a single CO2 cartridge can inflate the belt, however given the quantity of gas stored within the cartridge and comparatively low pressure requirement of the belt, we anticipate it will be high.

The Pneumatic Smart Adaptive Belt secured the jogging bottoms tightly on the wooden mannequin, however in future we plan to integrate the belt into a custom garment. This device will adhere to health and safety guidelines and will be used in studies with real users to provide feedback for future generations of Smart Adaptive Clothing.

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