Fashion and Textiles

RESEARCH Open Access

Development of a 4D hand gripping aid using a knitted shape memory alloy and evaluation of finger-bending angles in elderly women

Soo-Min Lee[1†], Woo-Kyun Jung[2†], Juyeon Park[1,2,3*] and Sung-Hoon Ahn[4,5*]

*Correspondence: juyeon.park@snu.ac.kr; ahnsh@snu.ac.kr
†Soo-Min Lee and Woo-Kyun Jung contributed equally to this work as the first author
[1] Department of Textiles, Merchandising and Fashion Design, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea
[4] Department of Mechanical Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea
Full list of author information is available at the end of the article

Abstract

As the global population ages, there is an increasing demand for physical assistive devices for the elderly. This study aimed to develop and evaluate a wearable gripping aid for elderly women to assist in their handgrip ability. We developed an actuator module for the hand-gripping aid using a 4D knitted shape memory alloy and attached to a flexible nylon glove. At baseline, we measured the bending angles of the knitted shape memory alloy and the subjects' fingers while gripping. The bending angles of the gripping aid demonstrated similar hand mobility to those of elderly women in real life. We also found that SMA modules attached to a glove could implement the bending angle when gripping a ball derived from the index and middle fingers of elderly women. The finding could help to develop hand products that could be worn on the hand of the elderly by realizing the bending motion of each finger. The outcomes of this study suggest the practical potential of this wearable device as an effective hand-gripping aid for the elderly, based on a novel 4D material and ergonomic design approach.

Keywords: 4D hand-gripping aid, Knitted shape memory alloy, Elderly

Introduction

The world is rapidly becoming an aging society as science and medical technology advance. The World Health Organization (WHO) predicts that the proportion of the world's elderly aged over 60 years, reported at 12% in 2015, will approximately double to 22% by 2050, and the rate of population aging will continue to increase (World Health Organization, 2018). As humans age, they experience a decline in physical performance due to physical and physiological changes, including nervous system decline and muscle loss (Carmeli et al., 2003; Ranganathan et al., 2001; Van Beek et al., 2019). In particular, hands provide important functionality in most daily activities, such as holding and moving objects. Therefore, weakened hand-grip strength may cause inconvenience in performing everyday tasks, such as writing, using zippers, opening doors, and buttoning clothes (Nordin & Frankel, 2001). Further, such a decrease in hand muscle strength is also correlated to a reduction in estrogen, which is more prone to occur in women than men (Collins et al., 2019). Therefore, women tend to experience more difficulties in their hand motion than men as they age.

Recently, various attempts have been made to develop assistive gripping devices for people with decreased hand muscle strength (Kang et al., 2019; Kazeminasab et al., 2018; Kim et al., 2017; Saharan et al., 2017; Yap et al., 2017). However, most efforts have focused on the development of exoskeleton devices, which are made of rigid materials, and are thus likely to put a strain on the human body. As an alternative solution to mitigate the wearability issue of rigid exoskeletons, softer and lighter materials have been adopted. However, the soft wearable approach seems to present its own limitations because they cannot provide sufficient force as opposed to exoskeleton devices. Therefore, we investigated the mechanical characteristics of a shape memory alloy (SMA) to gauge the material's potential in soft wearables, particularly as a hand-gripping aid for the elderly.

An SMA is an intelligent material with a structure that transforms into a memorized shape by changing the phase of the material by varying temperature. An SMA can be easily manufactured into plates composed of various thicknesses and widths, wires of several millimeters to tens of micrometers, and actuators of specific shapes. The desired mechanical properties and shapes of SMA materials can be realized through a diverse combination of nickel and titanium. These characteristics have been applied in diverse wearable devices intended to assist the human body, including a wrist-assist wearable robot using an SMA coil-spring actuator (Jeong et al., 2019), an ankle-assist smart fabric using an SMA-based actuator (Kim et al., 2020), an SMA-based auxiliary sleeve (Ammar et al., 2010), and a wearable garment integrating fabric muscles that can assist arm strength when lifting heavy objects (Park & Park, 2019).

There have been previous efforts to adopt SMAs in the development of gripping aids by trying to replicate human hand motions using the material. However, these efforts mostly focused on the development of grippers to be used in industrial settings or robots using a tendon-driven system to control force (Andrianesis & Tzes, 2015; Bundhoo et al., 2009; Price et al., 2007; Silva et al., 2019). To render the bending degrees and strengths of SMAs suitable for human hands, recent studies have examined the use of different stiffnesses for each finger joint (Liu et al., 2020) or attempting precise control by applying analytic methods and reinforcement learning (Liu et al., 2019; Simone et al., 2019). In doing so, researchers have combined SMAs with other materials that have different stiffnesses, such as paraffin and shape memory polymer, to increase the maximum gripping force or to selectively change the stiffness while maintaining flexibility in a low-stiffness state (Wang & Ahn, 2017; Wang et al., 2020).

Furthermore, some researchers have examined SMAs in the form of fabric- or knit-type actuators. For example, Liu et. al. (2020) investigated the heat and humidity characteristics of SMA fabrics. Yuen et. al. (2014) composed fabric by stitching an SMA onto the woven fabric to perform various driving motions. Research attention has also focused on the use of knitted SMA wire. For example, Han and Ahn (2017) proposed loop-linked soft morphing structures for soft robots. In addition, Granberry et. al. (2017, 2019) presented a method of designing a calf aid for preventing orthostatic hypotension and an SMA fabric that fits itself to the body using a knitted SMA structure. Eschen et.

al. (2020) summarized guidelines that can be applied when designing a device using a knitted SMA actuator. Nasir et. al. (2014) asserted the importance of comprehending static and dynamic motions of the human hand (including those of the fingers) for the application of fabric- or knit-type SMA actuators in hand-gripping aids.

Various methods have been adopted in previous research (Bain et al., 2015; Murai et al., 2018) to measure finger joint angles. For example, some studies reported high precision of a 3D motion-capture system and strain sensor and application of a high-density inertial measurement device in measuring the range of finger motion (Li et al., 2018; Reissner et al., 2019), but they seem to increase the complexity of experimental procedures and are more time-consuming. Some have proposed a simple, alternative measurement tool such as a smartphone-based angle measurement app and argued the app's advantage in speed as compared to a goniometer (Lee et al., 2018; Miyake et al., 2020; Zhao et al., 2020). However, this method is less accurate. In this study, we adopted automatic 3D scanning technology to generate accurate finger-bending angles. According to Nasir and Troynikov (2017), 3D scanning technology is practical in improving an assistive device's wearability based on an accurate understanding of the relationship between the wearable device and the human body. This 3D technology makes it possible to accurately derive surface characteristics such as curvature and bending angles by creating exact landmark points on the human body, provides a minimum error rate, and can obtain detailed differences in human body characteristics such as size, shape, and contour in a short time (Choi & Hong, 2015; Pang et al., 2018; Yu et al., 2013). With this technology, we intend to add a fourth element (time) to the 3D composition through shape transformation such as shrinking, expanding, folding, and unfolding the knit material, thus creating a 4D gripping aid that corresponds with changes in shape deformation over time (Du Toit et al., 2020).

We aimed to develop a hand-gripping aid in the form of a glove using a 4D knitted SMA for elderly women and evaluated its wearability based on finger-bending angles. This aid was fabricated by knitting SMA wires of several hundred micrometers thick. Specifically, in this study, we recruited elderly women because the age-related decline in hand function is more pronounced in women than in men (Choi et al., 2018). Based on the understanding of the gripping characteristics of elderly women and mechanical properties of the knitted SMA, a glove-type wearable gripping aid was designed and produced. To achieve the research goals, we first analyzed the bending properties of the knitted SMA module itself, then measured the finger-bending angles of elderly women when in gripping motion, and finally compared the bending angles of a gripping aid made of a knitted SMA module and those of the elderly women's natural finger movements. We hypothesized that the bending angles of the SMA-based gripping aid were not different from those of elderly women's fingers when they grip an object.

Methods

Participants

A total of nine Korean elderly women (N = 9) participated in this study. The study was approved by the participating university's Institutional Review Board Committee (IRB No. 1903/003-004), and all participants provided written informed consent prior to participation. The mean age of the participants was 66.7 ± 2.26 years old. All participants

Table 1 Physical characteristics of participants

Participants (N = 9)	Mean(SD)
Age (years)	66.7 (2.26)
Height (cm)	159.20 (2.90)
Weight (kg)	57.00 (5.54)

SD standard deviation

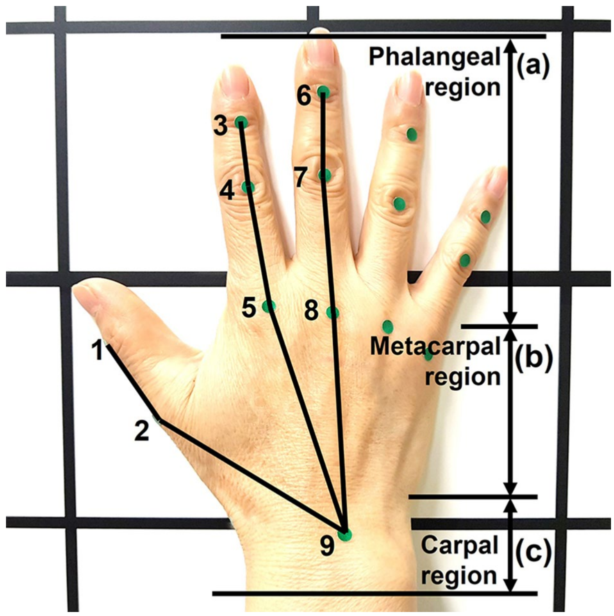

Fig. 1 Measurement positions and points on the participant's hand for 3D scanning. Phalangeal region, metacarpal region, and carpal region

were right-handed, and those with any hand injuries or abnormalities were excluded. Table 1 shows a summary of the participants' physical characteristics.

3D scan measurements of finger-bending angles

We measured the participants' finger-bending angles in a relaxed posture and a ball-gripping posture using 3D body-scanning technology. The regions of measurement are broadly divided into the finger, dorsal hand, and wrist regions, corresponding to the phalangeal (Fig. 1a), metacarpal (Fig. 1b), and carpal regions (Fig. 1c), respectively. Measurement points were marked at each finger joint of the thumb, index finger, and middle finger according to the anatomical position of the hand (Fig. 1). We included the distal interphalangeal and carpal bones (lunate bone close to the ulna and located in the center of the wrist) as anatomical landmark reference points for grip posture (LaBat & Ryan, 2019). Circular landmarks of 5 mm in diameter were attached to the measurement reference points set on the fingers and dorsal hand of the participants to minimize measuring errors.

Participants' hands were set to relaxed and ball-grip postures during 3D scanning as shown in Fig. 2. The relaxed posture (Fig. 2a) was set when the hand was comfortably

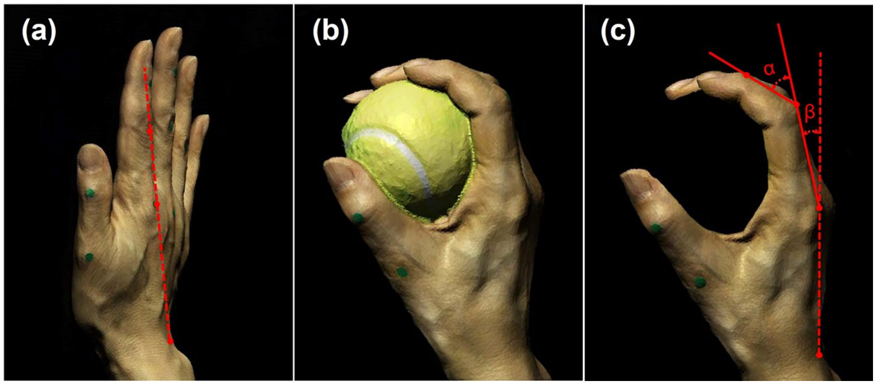

Fig. 2 Angle measurement posture and method using a 3D scanner. **a** Relaxed posture, **b** gripping a ball, and **c** grip posture for angle measurement (α: the external bending angle of the second joint connected to the first joint, and β: the external bending angle of the first joint)

Table 2 Landmark numbers for the 3D scanning measurement of angles

Finger	Thumb	Index		Middle	
		Proximal interphalangeal	Metacarpophalangeal	Proximal interphalangeal	Metacarpophalangeal
Landmark number	1–2–9	3–4–5 (α, °)	4–5–9 (β, °)	6–7–8 (α, °)	7–8–9 (β, °)

placed on the measurement desk without gripping anything. The ball-grip posture was measured using a tennis ball (diameter: 65 mm, weight: 56 g) (Fig. 2b, c). The participants were asked to hold the ball steadily and place their hands on the measurement desk. A 3D human-body scanner (Artec Eva; Artec 3D, Luxembourg) was used to extract 3D hand models and anthropometric measurements at the two postures, and data were extracted for each posture using software (Artec Studio 11 Professional; Artec 3D, Luxembourg). The vertex of the triangular mesh at the center of every landmark point was marked using design reverse-engineering software (Geomagic Design X; 3D Systems, Rock Hill, SC). This measurement method was adopted to minimize errors in the measurement. The landmark numbers according to fingers and joints are summarized in Table 2. The 3D measurements were repeated three times at each posture and data were presented as an average.

Data were statistically analyzed using SPSS 25.0 (IBM, Armonk, NY). Independent-samples t-tests were used to analyze the bending angles at the different hand regions and between the gripping aid and the participant's fingers. The significance level was set at $p < 0.05$.

Materials

An SMA wire (DYNALLOY Inc., Irvine, CA; 55 wt% Ni and 45 wt% Ti, diameter = 200 μm, transformation temperature = 70 °C) was used as the actuator material for the gripping aid. This wire was fabricated using a hand-knitting technique and the yarn was wrapped with polyester fiber, as described by Han and Ahn (2017), to prevent electric leakage between loops and to increase the coefficient of friction. In addition, the polyester fiber reduces the Joule heat generated during SMA deformation at about 70 °C, thereby preventing from burn injuries on the human body, as well as physical damages on materials. Knitted SMA fabrics tend to have a higher shrinkage than woven fabrics because they undergo a knitting process with high stress and expansion (Choi & Lo, 2003); thus, it was deemed suitable for a gripping-aid actuator for fingers with various joints.

The loops of the knitted SMA fabric were formed in succession and were continuously connected to the previous row. Among the various knitting techniques, the plain knitting pattern consists of knit stitches on one side and purl stitches on the other side, so it has a bending characteristic with a surface composed of knit stitches when actuated by a SMA material (Granberry et al., 2019; Han & Ahn, 2017). In this study, the bending of the fingers was simulated by a plain knitted structure considering the ratio of wale and course, utilizing the structural bending characteristics of a plain knitting pattern. Figure 3 shows the design and manufacture of the SMA actuator to be applied to the gripping aid.

Fabrication of the gripping aid

Through a preliminary parameter study of the wale and course of the knitted SMA module, an optimal wale-course combination that closely simulates the finger sizes and bending angles of the human hand at the grip motion was confirmed, and the knitted SMA module was fabricated. The results revealed that the bending angle of the thumb is relatively small compared to those of the index and middle fingers. Considering the gripping mechanism that acts as a support when gripping an object, the knitted SMA module was applied only to the index and middle fingers. The applied SMA module was manufactured using a 3.0 mm stainless-steel knitting needle. Taking the length and bending angle of each finger into account, the number of stitches for the index and middle fingers were set to be 3 wales × 18 courses and 3 wales × 20 courses, respectively.

The knitted SMA modules were attached to a glove by whip-stitching the loops on each end surface of the module fabric to the legs loops in the wale direction, and

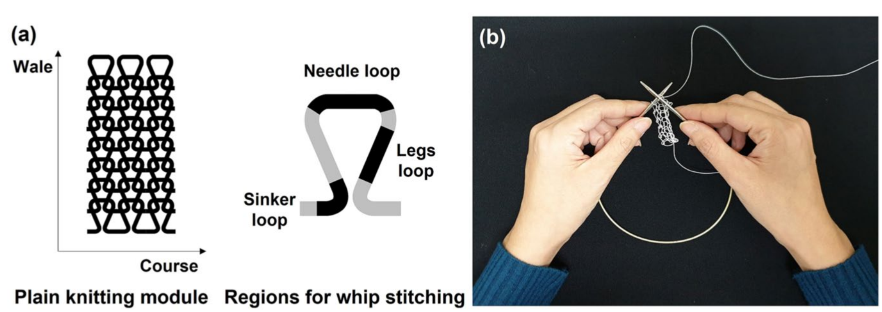

Fig. 3 Design and fabrication of shape memory alloy actuators. **a** Plain knitting module structure and **b** hand-knitting

needle and sinker loops in the course direction, considering the joint position of each finger (Figs. 3a and 4a). The base glove has large shrinkage so that the attached SMA module can implement the finger-bending angle when actuated and was selected as a material that can minimize the effect on hand agility when worn (composition: nylon 100%, size: medium). Figure 4b shows the appearance of the gripping aid with the knitted SMA module attached.

Measurement of bending angles of the SMA module and gripping aid

The bending characteristics of the two knitted SMA modules (i.e., index and middle modules) were analyzed. The top, middle, and bottom positions of the knitted SMA modules were situated in the wale direction at the same position as the distal, proximal interphalangeal, and metacarpophalangeal joints where finger landmarks were set. To measure the bending angles of the gripping aid while it was in actuation, pictures of the module were extracted by time-slot through video recording and the angles were measured from the side using a virtual protractor tool (Screen Protractor; Iconico Inc., Philadelphia, PA) (Fig. 5). A 3.0-A current was supplied to each module and actuated for 30 s, and the bending angle at each landmark was measured three times and averaged. Because the two proximal interphalangeal and metacarpophalangeal joints of the finger tend to create multifold angles at a gripping motion, we summed the angle values and used them in analysis.

In addition, the bending angles of the glove-type gripping aid with knitted SMA modules were also measured in the same manner as the module's bending angle measurement, as described above. A 3.0-A current was supplied to each of the knitted SMA modules on the index and middle fingers, and the changes in the bending angles of the gripping aid were measured over time. The gripping aid was operated for 30 s and the bending angle of each landmark was measured three times. The bending angles of the gripping aid were compared with the participants' finger-bending angles.

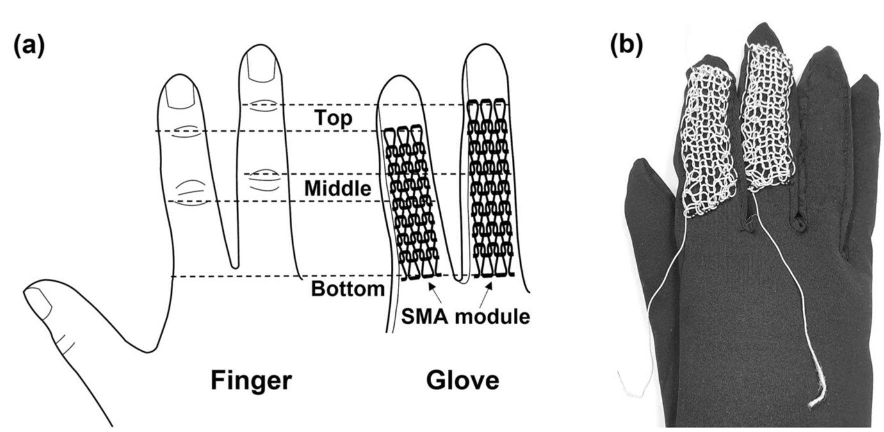

Fig. 4 Fabrication of the shape memory alloy (SMA) knitted module-based gripping aid. **a** Position of SMA knitted module on the glove and **b** fabricated gripping aid

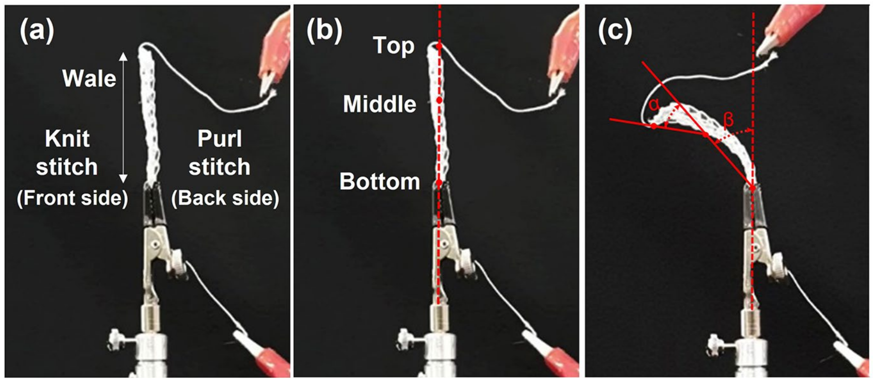

Fig. 5 Side-view of the knitted shape memory alloy module and method for angle measurement. **a** Stitch composition of plain knitted pattern, **b** measurement points, unactuated state, and **c** measurement points, actuated state (α: the external bending angle of the second joint connected to the first joint, and β: the external bending angle of the first joint)

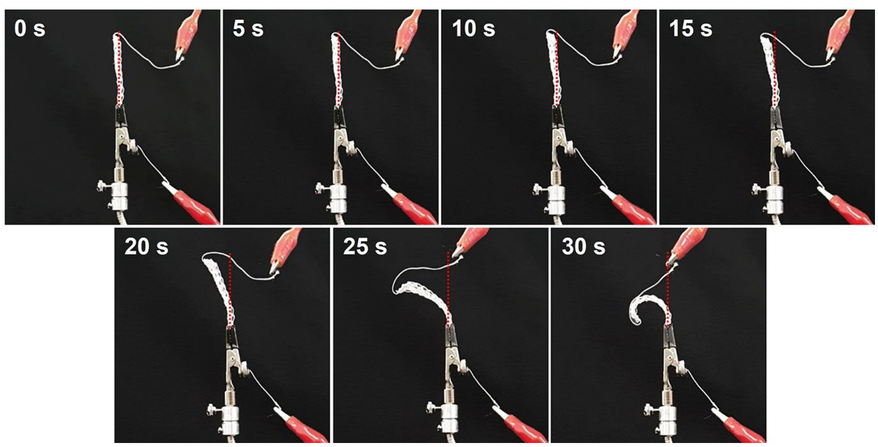

Fig. 6 Bending angle changes of the knitted shape memory alloy module over time

Results

Bending angle change of knitted SMA modules

The knitted SMA modules, which showed bending deformation from approximately 10 s after the electric current was applied, demonstrated the maximum bending angle at 30 s and were completely deformed (Fig. 6). Table 3 shows changes in bending angles of the knitted SMA modules over time. As a result, the longer (middle) module had larger bending angles due to an increase in the driving force (proximal interphalangeal = 73.73 ± 0.57°; metacarpophalangeal = 108.57 ± 1.63°), and the shorter (index) module had relatively smaller bending angles (proximal interphalangeal = 62.57 ± 2.32°; metacarpophalangeal = 78.47 ± 1.27°). The total bending angles were 141.04 ± 3.59° in the index module and 182.30 ± 2.20° in the middle module, respectively.

Table 3 Bending angle changes of the knitted shape memory alloy modules

Measurement landmark	Bending angle (°) by time						
	0 s	5 s	10 s	15 s	20 s	25 s	30 s
Proximal interphalangeal	0.00 (0.00)	0.00 (0.00)	7.40 (0.17)	12.13 (0.84)	22.17 (0.45)	49.93 (1.19)	62.57 (2.32)
Metacarpophalangeal	0.00 (0.00)	0.00 (0.00)	6.03 (0.15)	16.83 (0.38)	19.83 (0.55)	51.57 (1.58)	78.47 (1.27)
Total	0.00 (0.00)	0.00 (0.00)	13.43 (0.32)	28.96 (1.22)	42.00 (1.00)	101.50 (2.77)	141.04 (3.59)
Proximal interphalangeal	0.00 (0.00)	0.00 (0.00)	8.03 (1.80)	13.17 (0.90)	19.10 (1.35)	62.23 (0.95)	73.73 (0.57)
Metacarpophalangeal	0.00 (0.00)	0.00 (0.00)	7.07 (0.23)	16.80 (0.30)	28.00 (0.36)	62.43 (0.59)	108.57 (1.63)
Total	0.00 (0.00)	0.00 (0.00)	15.10 (2.03)	29.97 (1.20)	47.10 (1.71)	124.66 (1.54)	182.30 (2.20)

Data are expressed as Mean (SD)

SD standard deviation

Measurement of participants' finger-bending angles

Table 4 and Fig. 7 show the finger-bending angles of the participants in the ball-grip posture, specifically for the thumb, index, and middle fingers. The proximal

Table 4 Measurement results for participants' finger-bending angles

Target object	Landmark number	Bending angle (°) Mean (SD)	Total (°) Mean (SD)	*P* value
Thumb	1–2–9	35.21 (12.88)	–	–
Index finger				
Proximal interphalangeal	3–4–5	38.04 (11.79)	61.90 (18.20)	0.006
Metacarpophalangeal	4–5–9	23.86 (6.41)		
Middle finger				
Proximal interphalangeal	6–7–8	40.75 (11.24)	65.32 (20.09)	0.004
Metacarpophalangeal	7–8–9	24.57 (8.85)		

SD standard deviation

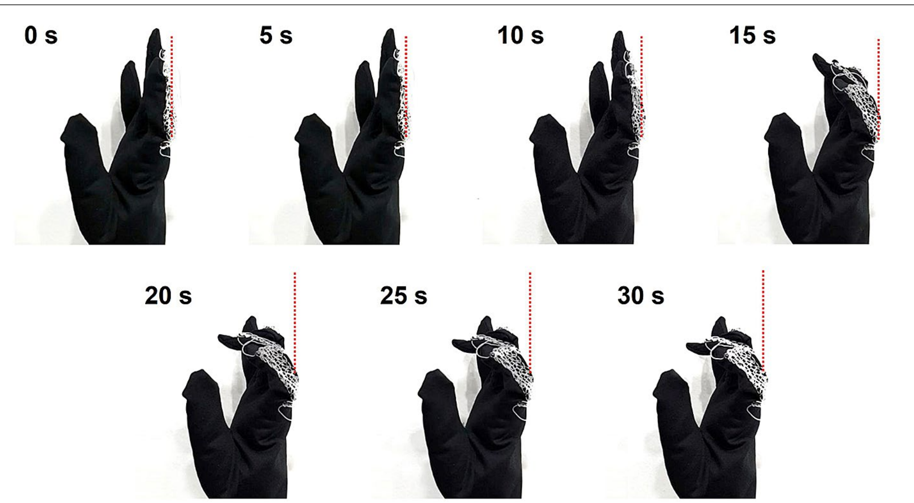

Fig. 7 Change in bending angle of the gripping aid over time

interphalangeal had a greater bending angle than the metacarpophalangeal in both index and middle fingers (index: $t = 3.170$, $p = 0.006$, middle: $t = 3.393$, $p = 0.004$). As suggested by the sum of the bending angles of the module, the bending angles at both hand regions (i.e., the total value of proximal interphalangeal and metacarpophalangeal) in the index and middle fingers were summed, which were $61.90 \pm 18.20°$ and $65.32 \pm 20.09°$, respectively. In other words, the total bending angle of the middle finger was relatively larger than that of the index. As these are similar to the results of the total bending angles of the SMA modules in "Bending angle change of knitted SMA modules" section, these index and middle modules were intended to be attached to the index and middle fingers of the glove, respectively.

Bending angle changes with the knitted SMA-based gripping aid

The bending angles of the gripping aid were measured for 30 s after applying a current of 0.3 A to each SMA module (Fig. 7). Table 5 compares the changes in the bending angles of the gripping aid over time relative to participants' finger-bending angles. The gripping aid started to deform at approximately 10 s after applying the current and showed maximum deformation at 30 s. The maximum deformation angle of the gripping aid was 91.30° in the index finger region and 104.47° in the middle finger region. The bending angle of the SMA module in Fig. 6 and the glove-type gripping aid in Fig. 7 show different maximum bending angles at 30 s. This is because while the SMA actuator module was attached to the glove, the bending was attenuated by the glove material, and the blocking force of the surface extension of the glove material was greater than that of the SMA actuator over the bending angles. This issue could be partially controlled through the glove material and the method of attaching the gloves and SMA actuator module. As discussed in "Measurement of participants' finger-bending angles" section, the middle-finger module was designed to be longer than the index-finger module, as middle fingers are longer than index fingers, resulting in a higher bending angle. The middle module showed an approximately 29% greater bending angle than the index module, and an approximately 14% greater bending angle in the gripping aid.

Figure 8, which illustrates the combined results of Tables 4 and 5, shows how the bending angles of the gripping aid are relative to the elderly women's finger movements. As shown in Table 5, after actuating the gripping aid for 30 s, we noticed that the bending angle of the index finger of the gripping aid was similar to that of participants' fingers at 25 s and the bending of the middle finger of the gripping aid was similar to that of participants' finger at 20 s. Therefore, we compared the data at 25 s for the index finger and 20 s for the middle finger. As for the index finger, at 25 s after actuating, the proximal interphalangeal of the gripping aid showed a bend angle of 36.23° and that of participants' fingers was 38.04°, which demonstrated a difference of approximately 4.7%. There was no significant difference between the bending angle of the proximal interphalangeal of the index finger in participants and that of the gripping aid ($t = 0.256$, $p = 0.803$). As for the middle finger, at 20 s after actuating, the proximal interphalangeal of the gripping aid showed a bend angle of 37.03° and that of participants' fingers was 40.75°. There was no significant difference between the bending angle of the proximal interphalangeal of the middle in participants and that of the gripping aid ($t = 0.987$, $p = 0.352$). As discussed earlier, we used the summed

Table 5 Bending angle change of the gripping aid compared with that of participants' fingers

Target object	Measurement landmark		Bending angle (°)	Target object	Bending angle (°) by time						
					0 s	5 s	10 s	15 s	20 s	25 s	30 s
Participant fingers Mean (SD)	Index	Proximal interphalangeal	**38.04 (11.79)**	Gripping aid Mean (SD)	0.00 (0.00)	0.00 (0.00)	8.53 (0.31)	19.10 (0.20)	29.03 (0.40)	**36.23 (1.55)**	54.77 (0.49)
		Metacarpophalangeal	**23.86 (6.41)**		0.00 (0.00)	0.00 (0.00)	7.40 (0.35)	18.13 (0.55)	25.67 (0.38)	**25.67 (0.38)**	36.53 (2.18)
		Total	**61.90 (18.20)**		0.00 (0.00)	0.00 (0.00)	15.93 (0.66)	37.23 (0.75)	54.70 (0.78)	**61.90 (1.93)**	91.30 (2.67)
	Middle	Proximal interphalangeal	**40.75 (11.24)**		0.00 (0.00)	0.00 (0.00)	7.87 (0.59)	20.13 (0.90)	**37.03 (0.68)**	49.57 (0.61)	65.40 (1.31)
		Metacarpophalangeal	**24.57 (8.85)**		0.00 (0.00)	0.00 (0.00)	4.23 (0.78)	22.80 (0.70)	**35.23 (0.40)**	36.90 (0.95)	39.07 (0.49)
		Total	**65.32 (20.09)**		0.00 (0.00)	0.00 (0.00)	12.10 (1.37)	42.93 (1.60)	**72.26 (1.08)**	86.47 (1.56)	104.47 (1.80)

Bold value indicates the bending angles of the gripping aid corresponding to those of the given finger

SD standard deviation

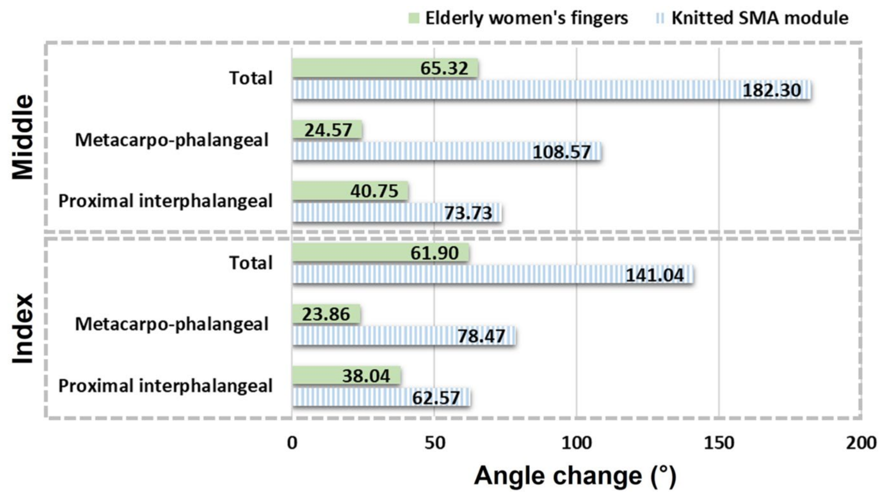

Fig. 8 Comparison of finger-bending angles for the gripping aid versus participant finger movements

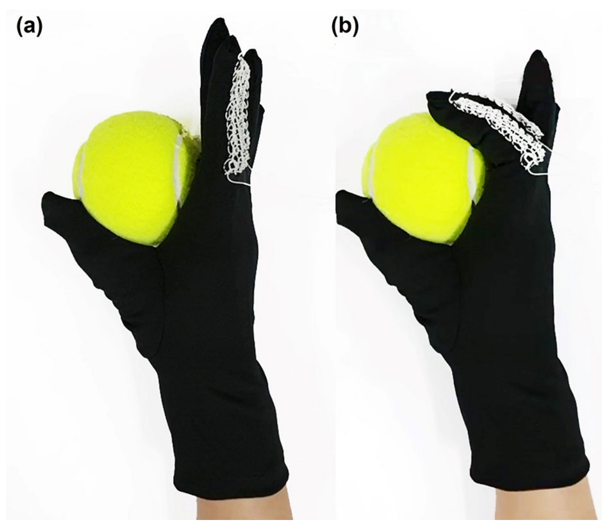

Fig. 9 Before and after actuating with a gripping aid on the hand of an elderly woman. (**a**) before actuation and (**b**) after actuation

values of all multifold angles created by the bending of the two finger joints when holding an object; that is, the total bending angle of the index finger in participants and that of the gripping aid were equal to the second decimal point. The total bending angle of the middle finger in participants and the gripping aid were 65.32° and 72.26°, respectively, with no significant difference ($t = -0.829$, $p = 0.426$). This indicates that a gripping aid based on a knitted SMA can implement a motion similar to that of gripping by participants, which supported the study hypothesis. Furthermore, Fig. 9 illustrates a hand of an elderly woman wearing the gripping aid and gripping a ball. We actuated it while the participant wore it on her hand at 0.3 A, as when driving only the gripping aid. Finally, we confirmed that the fingers were bent only with the driving force of the gripping aid without applying force to the hand when an elderly woman wore the gripping aid with the SMA module attached.

Discussion

This study presented a method of applying a knitted SMA actuator to the finger as an assist device along with an ergonomic approach to mimic the bending angle of elderly fingers. As the knitted SMA module we designed was actuated, the shape deformation of the knit loops connected to each other showed bending characteristics. We derived anthropometric data to reproduce the bending angle of the elderly finger by applying the fourth element of time to this intelligent material and applying shape deformation characteristics (i.e., bending) over time. We measured the exact bending angle of the joints from the 3D shape of the elderly female fingers in the grip posture obtained using a 3D scanner. Although there are various studies measuring finger-bending angles (Bain et al., 2015; Miyake et al., 2020; Murai et al., 2018; Reissner et al., 2019; Zhao et al., 2020), no attempt to date has been made to extract the exact angle on the 3D finger model using 3D scanning technology. Through this, we found that the assistive aid developed in this study can accurately simulate the bending angle of fingers of elderly women. This approach is suggested to be used in developing assistive devices that could be applied to larger parts of the human body.

Additionally, we found differences between the index- and middle-finger joint angles and the proximal and metacarpophalangeal joint angles when the elderly women gripped a ball. We found that SMA modules attached to a glove can implement the bending angle when gripping a ball derived from the index and middle fingers of elderly women. In particular, at the proximal interphalangeal joint, the middle module was driven faster than the index module, which realized the bending angle of the finger in 20 s. This is because the middle module has more loops in the wale direction than the index module. It could also be due to the effect of the direction of current flow and the greater driving force (Bhargaw et al., 2013). Finally, we found that these modules could be worn on the hand of an elderly woman and operated by actuating the gripping aid to realize the bending motions of the fingers.

Conclusions

This study discovered the mechanical properties of knitted SMA modules through an ergonomic method and was able to simulate the bending of elderly finger joints. However, the grip movement of the human hand involves not only the bending of the finger but also a combination of other factors such the stiffness of materials, the frictional force between the surface of the object, and the point where the gripping aid can withstand the weight of the object. Further, for postmenopausal elderly women, the skin surface changes caused by the decrease in skin tissues, due to collagen loss, should also be taken into consideration when developing a wearable hand gripping aid (Lee, 2019; Tobin, 2017). In this study, the bending angle was implemented through a fabric-type bending module with a curvature, but additional research is needed to investigate the implementation of joint folding through a combination of modules. The SMA actuator module was manufactured through hand-knitting, but to mass-produce modules with the same performance, it is necessary to devise a mechanical module-manufacturing method. In addition, to utilize a gripping aid as a mobile wearable device, further research should be conducted into ergonomic factors (such as finger strength, fingertip pressure, and joint fold) and power supply for the utilization of wearable devices that will contribute to the realization of effective gripping aids for elderly women, which are essential in an aging society. In conclusion, the outcomes of this study suggest the practical potential of our developed wearable device as an effective hand-gripping aid for the elderly, based on a novel 4D material and ergonomic design approach.

Acknowledgements
Not applicable.

Authors' contributions
All authors collaboratively contributed to the design, planning, and execution of the research project. SL and WJ as the first authors were responsible for collecting and analysing the data and writing the first draft of the manuscript. JP and SA supervised the overall research process and reviewed and revised the manuscript. All authors read and approved the final manuscript.

Authors' information
Soo-Min Lee is a Ph.D. candidate in the Department of Textiles, Merchandising and Fashion Design at Seoul National University. She received her Master's degree from the same department/university in 2019. Her research interests include development of ergonomic products and fabrication of various knitting patterns with shape memory alloy.
Woo-Kyun Jung, Ph.D. is a Research Assistant Professor in the Soft Robotics Research Center at Seoul National University. He received a Ph.D. degree in Mechanical Engineering from the same university in 2020. His research interests are in soft robotics, smart/composite materials, smart factory, and appropriate technology.
Juyeon Park, Ph.D. is an Associate Professor in the Department of Textiles, Merchandising and Fashion Design and a Vice Director of the Soft Robotics Research Center at Seoul National University. Her research scholarship focuses on human-centered design, ergonomic development of wearable products, and human body anthropometry.
Sung-Hoon Ahn, Ph.D. is a Professor in the Department of Mechanical Engineering at Seoul National University. His research interests include micro/nano fabrications, soft robotics, 3D printing, smart factory, green manufacturing, composite materials, renewable energy, and appropriate technology.

Funding
This work was supported by Seoul National University Research Grant in 2021 and the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIT) (2016R1A5A1938472).

Availability of data and materials
Raw data (image files and samples) generated for this study are available upon request from the corresponding author.

Declarations

Ethics approval and consent to participate
The authors declared that this research was conducted with approval of Institutional Review Board. The IRB has been approved by Seoul National University Institutional Review Board (SNU IRB) and the approval number is IRB No. 2009/003-021.

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Department of Textiles, Merchandising and Fashion Design, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea. [2]Soft Robotics Research Center, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea. [3]Research Institute of Human Ecology, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea. [4]Department of Mechanical Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea. [5]Institute of Advanced Machines and Design, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea.

Received: 13 June 2021 Accepted: 13 October 2021
Published online: 05 April 2022

References

Ammar, L. I., Kaddouh, B. Y., Mohanna, M. K., & Elhajj, I. H. (2010). SAS: SMA aiding sleeve. In *2010 IEEE International Conference on Robotics and Biomimetics, Tianjin, China*. https://doi.org/10.1109/ROBIO.2010.5723568
Andrianesis, K., & Tzes, A. (2015). Development and control of a multifunctional prosthetic hand with shape memory alloy actuators. *Journal of Intelligent & Robotic Systems, 78*, 257–289. https://doi.org/10.1007/s10846-014-0061-6

Bain, G. I., Polites, N., Higgs, B. G., Heptinstall, R. J., & McGrath, A. M. (2015). The functional range of motion of the finger joints. *Journal of Hand Surgery, European, 40*(4), 406–411. https://doi.org/10.1016/0363-5023(90)90102-W

Bhargaw, H. N., Ahmed, M., & Sinha, P. (2013). Thermo-electric behaviour of NiTi shape memory alloy. *Transactions of Nonferrous Metals Society of China, 23*(8), 2329–2335. https://doi.org/10.1016/S1003-6326(13)62737-5

Bundhoo, V., Haslam, E., Birch, B., & Park, E. J. (2009). A shape memory alloy-based tendon-driven actuation system for biomimetic artificial fingers, part I: Design and evaluation. *Robotica, 27*(1), 131–146. https://doi.org/10.1017/S026357470800458X

Carmeli, E., Patish, H., & Coleman, R. (2003). The aging hand. *The Journals of Gerontology: Series A, 58*(2), 146–152. https://doi.org/10.1093/gerona/58.2.M146

Choi, J., & Hong, K. (2015). 3D skin length deformation of lower body during knee joint flexion for the practical application of functional sportswear. *Applied Ergonomics, 48*, 186–201. https://doi.org/10.1016/j.apergo.2014.11.016

Choi, K. H., Kim, D. M., Lee, S. Y., Lee, J. H., & Kong, Y. K. (2018). Evaluation of the controlled grip force exertion tasks associated with age, gender, handedness and target force level. *International Journal of Occupational Safety and Ergonomics, 24*(4), 507–515. https://doi.org/10.1177/004051750307300813

Choi, K. F., & Lo, T. Y. (2003). An energy model of plain knitted fabric. *Textiles Research Journal, 73*(8), 739–748. https://doi.org/10.1080/10803548.2017.1322832

Collins, B. C., Laakkonen, E. K., & Lowe, D. A. (2019). Aging of the musculoskeletal system: How the loss of estrogen impacts muscle strength. *Bone, 123*, 137–144. https://doi.org/10.1016/j.bone.2019.03.033

Du Toit, L. C., Kumar, P., Choonara, Y. E., & Pillay, V. (Eds.). (2020). *Advanced 3D-printed systems and nanosystems for drug delivery and tissue engineering*. Elsevier.

Eschen, K., Granberry, R., & Abel, J. (2020). Guidelines on the design, characterization, and operation of shape memory alloy knitted actuators. *Smart Materials and Structures*. https://doi.org/10.1088/1361-665X/ab6ba7

Granberry, R., Abel, J., & Holschuh, B. (2017). Active knit compression stockings for the treatment of orthostatic hypotension. In *Proceedings of the 2017 ACM international symposium on wearable computers ISWC Part F1305* (pp. 186–191). https://doi.org/10.1145/3123021.3123065

Granberry, R., Eschen, K., Holschuh, B., & Abel, J. (2019). Functionally graded knitted actuators with NiTi-based shape memory alloys for topographically self-fitting wearables. *Advanced Materials Technologies, 4*(11), 1–11. https://doi.org/10.1002/admt.201900548

Han, M. W., & Ahn, S. H. (2017). Blooming knit flowers: Loop-linked soft morphing structures for soft robotics. *Advanced Materials, 29*(13), 1–6. https://doi.org/10.1002/adma.201606580

Jeong, J., Yasir, I. B., Han, J., Park, C. H., Bok, S. K., & Kyung, K. U. (2019). Design of shape memory alloy-based soft wearable robot for assisting wrist motion. *Applied Sciences, 9*(19), 4025. https://doi.org/10.3390/app9194025

Kang, B. B., Choi, H., Lee, H., & Cho, K. J. (2019). Exo-Glove Poly II: A polymer-based soft wearable robot for the hand with a tendon-driven actuation system. *Soft Robotics, 6*(2), 214–227. https://doi.org/10.1089/soro.2018.0006

Kazeminasab, S., Hadi, A., Alipour, K., & Elahinia, M. (2018). Force and motion control of a tendon-driven hand exoskeleton actuated by shape memory alloys. *Industrial Robot, 45*(5), 623–633. https://doi.org/10.1108/IR-01-2018-0020

Kim, B., In, H., Lee, D. Y., & Cho, K. J. (2017). Development and assessment of a hand assist device: GRIPIT. *Journal of Neuroengineering and Rehabilitation, 14*(1), 1–14. https://doi.org/10.1186/s12984-017-0223-4

Kim, C., Kim, G., Lee, Y., Lee, G., Han, S., Kang, D., Koo, S. H., & Koh, J. S. (2020). Shape memory alloy actuator-embedded smart clothes for ankle assistance. *Smart Materials and Structures*. https://doi.org/10.1088/1361-665X/ab78b5

LaBat, K. L., & Ryan, K. S. (2019). *Human body: A wearable product designer's guide*. CRC Press.

Lee, S. (2019). Analysis of hand forces and surface changes based on pinch postures of elderly women and women in their 20s (Master's dissertation, Seoul National University, Seoul, Republic of Korea).

Lee, H. H., St. Louis, K., & Fowler, J. R. (2018). Accuracy and reliability of visual inspection and smartphone applications for measuring finger range of motion. *Orthopedics, 41*(2), e217–e221. https://doi.org/10.3928/01477447-20180103-02

Li, X., Wen, R., Shen, Z., Wang, Z., Luk, K. D. K., & Hu, Y. (2018). A wearable detector for simultaneous finger joint motion measurement. *IEEE Transactions on Biomedical Circuits and Systems, 12*(3), 644–654. https://doi.org/10.1109/TBCAS.2018.2810182

Liu, M., Hao, L., Zhang, W., Chen, Y., & Chen, J. (2019). Reinforcement learning control of a shape memory alloy-based bionic robotic hand. In *2019 IEEE 9th IEEE international conference on CYBER technology in automation, control, and intelligent systems (CYBER), Suzhou, China*. https://doi.org/10.1109/CYBER46603.2019.9066775

Liu, M., Hao, L., Zhang, W., & Zhao, Z. (2020). A novel design of shape-memory alloy-based soft robotic gripper with variable stiffness. *International Journal of Advanced Robotic Systems, 17*(1), 1–12. https://doi.org/10.1177/1729881420907813

Miyake, K., Mori, H., Matsuma, S., Kimura, C., Izumoto, M., Nakaoka, H., & Sayama, K. (2020). A new method measurement for finger range of motion using a smartphone. *Journal of Plastic Surgery and Hand Surgery, 54*(4), 207–214. https://doi.org/10.1080/2000656X.2020.1755296

Murai, T., Uchiyama, S., Nakamura, K., Ido, Y., Hata, Y., & Kato, H. (2018). Functional range of motion in the metacarpophalangeal joints of the hand measured by single axis electric goniometers. *Journal of Orthopaedic Science, 23*(3), 504–510. https://doi.org/10.1016/j.jos.2018.01.013

Nasir, S. H., Troynikov, O., & Massy Westropp, N. (2014). Therapy gloves for patients with rheumatoid arthritis: A review. *Therapeutic Advances in Musculoskeletal Disease, 6*(6), 226–237. https://doi.org/10.1177/1759720X14557474

Nasir, S. H., & Troynikov, O. (2017). Influence of hand movement on skin deformation: A therapeutic glove design perspective. *Applied Ergonomics, 60*, 154–162.

Nordin, M., & Frankel, V. H. (Eds.). (2001). *Basic biomechanics of the musculoskeletal system*. Lippincott Williams & Wilkins.

Pang, T. Y., Lo, T. S. T., Ellena, T., Mustafa, H., Babalija, J., & Subic, A. (2018). Fit, stability and comfort assessment of custom-fitted bicycle helmet inner liner designs, based on 3D anthropometric data. *Applied Ergonomics, 68*, 240–248. https://doi.org/10.1016/j.apergo.2017.12.002

Park, S. J., & Park, C. H. (2019). Suit-type wearable robot powered by shape-memory-alloy-based fabric muscle. *Scientific Reports, 9*, 1–8. https://doi.org/10.1038/s41598-019-45722-x

Price, A. D., Jnifene, A., & Naguib, H. E. (2007). Design and control of a shape memory alloy based dexterous robot hand. *Smart Materials and Structures*. https://doi.org/10.1088/0964-1726/16/4/055
Ranganathan, V. K., Siemionow, V., Sahgal, V., & Yue, G. H. (2001). Effects of aging on hand function. *Journal of the American Geriatrics Society, 49*(11), 1478–1484. https://doi.org/10.1046/j.1532-5415.2001.4911240.x
Reissner, L., Fischer, G., List, R., Taylor, W. R., Giovanoli, P., & Calcagni, M. (2019). Minimal detectable difference of the finger and wrist range of motion: Comparison of goniometry and 3D motion analysis. *Journal of Orthopaedic Surgery and Research, 14*(1), 1–10. https://doi.org/10.1186/s13018-019-1177-y
Saharan, L., De Andrade, M. J., Saleem, W., Baughman, R. H., & Tadesse, Y. (2017). IGrab: Hand orthosis powered by twisted and coiled polymer muscles. *Smart Materials and Structures*. https://doi.org/10.1088/1361-665X/aa8929
Silva, A., De Oliveira, S., Ries, A., Silva, S. A., & Souto, C. (2019). A fuzzy logic control system for a robotic hand driven by shape memory alloy wires. *European Journal of Engineering and Technology Research, 4*(10), 173–178.
Simone, F., Rizzello, G., & Seelecke, S. (2019). A finite element framework for a shape memory alloy actuated finger. *Journal of Intelligent Material Systems and Structures, 30*(14), 2052–2064. https://doi.org/10.1177/1045389X19861787
Tobin, D. J. (2017). Introduction to skin aging. *Journal of Tissue Viability, 26*(1), 37–46. https://doi.org/10.1016/j.jtv.2016.03.002
Van Beek, N., Stegeman, D. F., Jonkers, I., de Korte, C. L., Veeger, D., & Maas, H. (2019). Single finger movements in the aging hand: Changes in finger independence, muscle activation patterns and tendon displacement in older adults. *Experimental Brain Research, 237*(5), 1141–1154. https://doi.org/10.1007/s00221-019-05487-1
Wang, W., & Ahn, S. H. (2017). Shape memory alloy-based soft gripper with variable stiffness for compliant and effective grasping. *Soft Robotics, 4*(4), 379–389. https://doi.org/10.1089/soro.2016.0081
Wang, W., Yu, C. Y., Abrego Serrano, P. A., & Ahn, S. H. (2020). Shape memory alloy-based soft finger with changeable bending length using targeted variable stiffness. *Soft Robotics, 7*(3), 283–291. https://doi.org/10.1089/soro.2018.0166
World Health Organization. (2018). Ageing and health. https://www.who.int/news-room/fact-sheets/detail/ageing-and-health. Accessed 28 December 2020.
Yap, H. K., Lim, J. H., Nasrallah, F., & Yeow, C. H. (2017). Design and preliminary feasibility study of a soft robotic glove for hand function assistance in stroke survivors. *Frontiers in Neuroscience, 11*, 547. https://doi.org/10.3389/fnins.2017.00547
Yu, A., Yick, K. L., Ng, S. P., & Yip, J. (2013). 2D and 3D anatomical analyses of hand dimensions for custom-made gloves. *Applied Ergonomics, 44*, 381–392. https://doi.org/10.1016/j.apergo.2012.10.001
Yuen, M., Cherian, A., Case, J. C., Seipel, J., & Kramer, R. K. (2014). Conformable actuation and sensing with robotic fabric. In *2014 IEEE/RSJ international conference on intelligent robots and systems (IROS 2014), Chicago, IL, USA*. https://doi.org/10.1109/IROS.2014.6942618
Zhao, J. Z., Blazar, P. E., Mora, A. N., & Earp, B. E. (2020). Range of motion measurements of the fingers via smartphone photography. *The Hand, 15*(5), 679–685. https://doi.org/10.1177/1558944718820955

Publisher's Note