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ORIGINAL ARTICLE

Comfort of two shoulder actuation mechanisms for arm therapy exoskeletons: a comparative study in healthy subjects

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Abstract Robotic exoskeletons can be used to study and treat patients with neurological impairments. They can guide and support the human limb over a large range of motion, which requires that the movement trajectory of the exoskeleton coincide with the one of the human arm. This is straightforward to achieve for rather simple joints like the elbow, but very challenging for complex joints like the human shoulder, which is comprised by several bones and can exhibit a movement with multiple rotational and translational degrees of freedom. Thus, several research groups have developed different shoulder actuation mechanism. However, there are no experimental studies that directly compare the comfort of two different shoulder actuation mechanisms. In this study, the comfort and the naturalness of the new shoulder actuation mechanism of the ARMin III exoskeleton are compared to a ball-and-socket-type shoulder actuation. The study was conducted in 20 healthy subjects using questionnaires and 3D-motion records to assess comfort and naturalness. The results indicate that the new shoulder actuation is slightly better than a ball-and-socket-type actuation. However, the differences are small, and under the tested conditions, the comfort and the naturalness of the two tested shoulder actuations do not differ a lot.

Keywords Arm therapy robot · Exoskeleton · Shoulder actuation · Comfort

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1 Introduction

1.1 Arm rehabilitation exoskeletons

Rehabilitation robots have become an important tool in neurorehabilitation. They are used to study and treat patients with neurological impairments [1, 2]. These devices are either end-effector-based, exoskeletons, or of a hybrid type [3, 4]. End-effector-based robots are connected to the patient's hand or forearm at one point, and depending on the number of links of the robots, the human arm can be positioned and orientated in the space. Examples for end-effector-based robots are the MIT-Manus [5], the Mirror Image Motion Enabler [6], the Bi-Manu-Track [7], the GENTLE/s [8], and the Arm Coordination Training Robot [9]. The mechanical structure of exoskeleton robots resembles the human arm anatomy, and the robot's links correspond with the human joint. Consequently, the human arm can be attached to the exoskeletons at several points.

Some examples of arm rehabilitation exoskeletons include the Dampace [10], the Armeo (former T-Wrex) [11], the MGA-Exoskeleton [12], the L-Exos [13], the Caden-7 [14], the Intelligent Robotic Arm [15], and the ARMin II and III [16] devices. The hybrid type refers to a combination of exoskeleton and end-effector-based. In this configuration, the proximal joints (i.e. shoulder) are typically actuated by an end-effector-based structure, and the distal joints (i.e. lower arm, wrist) are actuated by an exoskeleton. Examples are the MIT-Manus with wrist extension module [17] and the GENTLE/s with extension module [18].

Exoskeleton robots can be further classified into passive and active devices. Passive exoskeletons are mechanical devices that connect to the human arm and facilitate movements by passive weight supports (i.e. with springs or counter weights). Some passive exoskeletons use brakes to resist against the movement and make it more challenging for the patient to move its arm. A common therapy method is to use a virtual reality (VR) system to represent graphical tasks that the patient needs to fulfill (i.e. manipulating virtual objects) [16]. When combined with a VR system, the position sensors of the exoskeleton can measure the position and orientation of the real arm. This data can then be used to control objects (i.e. a virtual arm) in the virtual environment (i.e. a game). Active exoskeletons are equipped with motors that support or resist the movement of the patients in all directions. Position and force sensors for each motorized link are used to measure the patient's reaction [16]. Most active exoskeletons are combined with VR systems to visualize training tasks. Both passive and active exoskeletons are connected at several points to the human arm, implementing a close contact between the robot and the human arm. This has the advantage that exoskeletons can guide and support the arm in all positions, but raises the challenge that the movement of the exoskeleton must coincide with the movement of the human arm, and there should be no misalignment between the two. To achieve a comfortable and natural movement, the movement trajectory of the human arm with the exoskeleton should be the same as during natural movement without exoskeleton.

As a consequence, an exoskeleton must be well-aligned, adapted to the patient's arm length, and the mechanical construction must be adapted to the anatomical structure. This is fairly easy to achieve for simple joints like the elbow, but very challenging for complex joints, especially the human shoulder. A common oversimplification that can lead to misalignment between the robot and the human is the definition of a ball-and-socket-type joint for describing the movement of the human shoulder. While this assumption nearly holds for small angles exerted, it significantly deviates for larger motions [19].

1.2 Mechanisms to actuate the human shoulder

In the human shoulder, the humerus bone connects to the scapula via the glenohumeral joint, the scapula connects to the clavicle via the acromioclavicular joint, and the clavicle connects to the thorax via the sternoclavicular joint. Arm abduction is a combination of rotation of the humerus around the glenohumeral joint, the scapula around the acromioclavicular joint, and the clavicle around the sternoclavicular joint. As a consequence, besides of the three predominantly rotational movements, the humerus head undergoes an additional translational movement. The amplitude of the translational movement (in the vertical direction (-z coordinate), Figure 1), during an arm abduction ranges from 0 to 180° and is approximately 124 mm in the vertical direction for a person with 1.7 m body hight [20]. During a partial arm abduction ranging from 60 to 110°, the expected translation will be approximately 28 mm. A ball-and-socket-type robotic shoulder actuation does not account for translational movement, since it is capable of rotational motion only, which leads to misalignment. For the person wearing the exoskeleton, misalignment will create shear forces, which will cause slip between the robot attachments (cuffs) and the limb. This can create discomfort [19] and a reduced feeling of naturalness. It can lead to pressure sores on the skin of the patient, and in addition, long-term damage to the human joint could take place. Especially in patients suffering from decreased muscular strength, joint dislocations and cartilage damage could occur [19].

In a recent review, nine exoskeleton-based robotic rehabilitation systems providing a shoulder actuation have been identified [3]. Four devices do not account for translational movements of the shoulder joint. These are the KIST device [21], the L-Exos device [13], the Rupert device [22], and the Armin I device [16, 23]. The remaining five devices account for translational movements, namely the Dampace device [10], the MGA [12], the Pneu-Wrex [24], the T-Wrex [11, 25], the ARMin II [16, 26, 27], and the ARMin III [20] device. The question how different shoulder actuation mechanisms compare to each other with respect to users' comfort is an important one.

1.2.1 Open research question

From a biomechanical point of view, a shoulder actuation that accounts for translational movements should create fewer misalignments than shoulder actuations without translational movements. Therefore, the first should be more comfortable than the second, and the arm movement should feel more natural [19, 28, 29]. However, there are no experimental studies directly comparing the comfort of different shoulder actuation mechanisms. In this paper, we

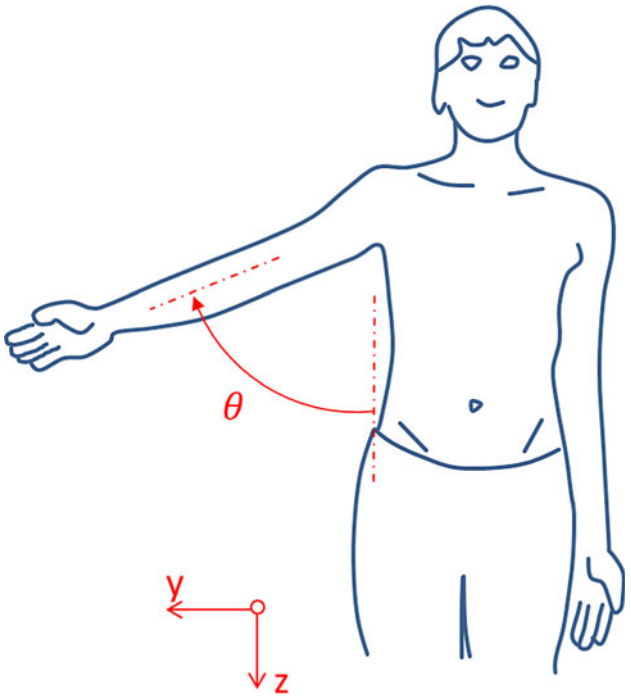

Fig. 1 The participants performed arm abduction movements in the frontal plane (z-y-plane) with fully extended elbow. The angle θ denotes the arm abduction angle

address this issue, and we directly compare the feeling of comfort in an exoskeleton that accounts for translational movements (in the vertical direction, -z vector, Fig. 1) of the shoulder versus an exoskeleton that does not account for it. Since shoulder actuation is one of the most challenging and most expensive parts when constructing an exoskeleton for the human arm, this research question is of great interest for the field of upper limb rehabilitation robotics.

For that purpose, we have constructed the ARMin III device with a modifiable shoulder actuation mechanism. Hence, the operator can select the shoulder actuation between either "translational movement off" (Toff) or "translational movement on" (Ton). Two hypotheses will be tested: Hypothesis 1: the comfort in operation mode Ton is higher than in operation mode Toff. And Hypothesis 2: the naturalness in operation mode Ton is higher than in operation mode Toff. The outcome measures of the study are the results of a questionnaire about subjects feeling of comfort as well as the motion trajectory of the acromion that will be compared between Ton and Toff.

2 Methods

2.1 Mechanical setup

The experiment was performed with the ARMin III robotic exoskeleton [20, 30]. The version that was used for this study as shown in Figure is equipped with six electric motors to actuate the shoulder (three motors), the elbow (one motor), lower arm pronation and supination (one motor), and wrist flexion and extension (one motor). The device can be used for the right and the left arm. For this experiment, it was used in the right arm configuration. Motor (1) rotates the plane of the arm abduction/adduction movement, motor (2) arm abduction/adduction, and motor (3) internal/external shoulder rotation [31]. Two laser diodes (5 and 6) help the therapist to position the shoulder of the test person. The test person is positioned in the device so that the center of the humerus head is located at the intersection point of the vertical (6, 7) and the horizontal laser beam (5, 8).

The arm is fixed to the exoskeleton via two size-adaptable cuffs. One cuff connects to the upper arm and one cuff to the lower arm (just before the wrist joint). The elbow joint lies on a cushion that is mounted to the robotic elbow joint. As it is shown in Fig. 2, the hand grasps the cushioned hand bar.

With the aim to realize an ergonomic shoulder actuation that accounts for the rotational and the translational movement of the humerus head, the link that contains motor (2) can be fixated at different positions ranging from $\phi = \pm 40°$. This can be achieved with the screw (2) in Fig. 2. It results in a displacement r between the arm abduction axis (9) and the humerus head, which is in line with the light emitted by diode (5) (Fig. 2b). If the therapist selects $\phi = 0°$, the displacement is $r = 0$ resulting in a ball-and-socket-type shoulder actuation with pure rotation. In this case, according to earlier work [20], the mean value of the misalignment occurring during an arm abduction from 60 to 110° is 7.1 mm for a person with 1.7 m body height [20, 32]. When selecting $\phi = 9.1°$, the displacement becomes $r = 2\pi \cdot 360^{-1} q_3 \phi = 2\pi \cdot 360^{-1} \cdot 228\text{mm} \cdot 9.1° = 36\text{mm}$, which results in a vertical translational movement of the humerus head, and the misalignment is reduced to the mean value 2.7 mm [20]. The size of the angle ϕ determines the translational movement (in the vertical direction) of the humerus head and should be selected according to the body size according to

$$\phi = \arcsin\left(\frac{d_{\text{ref}}}{q_3} \cdot \frac{h_{\text{body}}}{h_{\text{ref}}}\right) = \arcsin\left(\frac{0.036\text{m}}{0.228\text{m}} \cdot \frac{h_{\text{body}}}{1.7\text{m}}\right) = \arcsin\left(0.0929 \cdot h_{\text{body}}\right) \quad (1)$$

Formula [1] is from previous work and details on how to estimate ϕ can be found in [20]. For this study, two mechanical settings were tested: The setting ball-and-socket-joint without translational motion (Toff) with $\phi = 0°$ and the setting with translational motion (Ton) where the angle ϕ is selected based on the body size h_{body} according to Eq. (1). The shoulder mechanism also allows

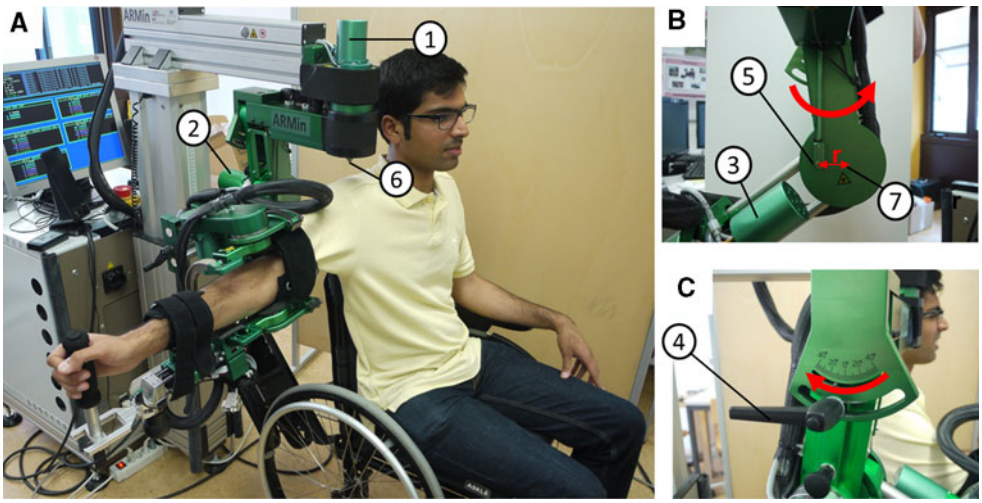

Fig. 2 **a** Shows the ARMin III device with a healthy test person. **b** Shows the front-side (from the patient's viewpoint) of the shoulder actuation. **c** Shows the backside of the shoulder actuation with the mechanism to change the angle ϕ. The ARMin device is equipped with six electrical motors to actuate the shoulder, the elbow, lower arm pro- and supination, and wrist flexion and extension. The shoulder mechanism consists of three motors (*1*), (*2*), and (*3*). Two laser diodes (*5*) and (*6*) help to correctly position the user. A special feature of the shoulder actuation is that by untightening the screw (*4*), the link that contains motor (*2*) can be tilted by the angle $\phi \pm 40°$, which results in a displacement r between the arm abduction axis (*7*) and the humerus head. For configuration Ton, the angle ϕ is selected according to the users' body height using equation [1]. For configuration Toff, the angle $\phi = 0°$

doing a "sham" manipulation, where the fixation is released and afterward fixated in the very same position as before. The test person cannot distinguish between sham and real manipulation. Thus, the following four conditions can be tested Ton following Ton (with sham manipulation), Ton following Toff (with real manipulation), Toff following Ton (with real manipulation), and Toff following Toff (with sham manipulation).

2.2 Participants

After approval of the institutional review board of the National Rehabilitation Hospital in Washington D.C., 20 healthy subjects (mean age 29.6 ± 9.1) were included in the study. After written informed consent was collected, participants were randomly assigned to group 1 or group 2. The protocol for the two groups was the same, except that the order of the mechanical settings to be tested was altered.

2.3 Experimental protocol

At the beginning of the experiment, the participants were seated in a wheelchair and the ARMin device was adjusted to the participants. Namely, the shoulder height and the lower and upper arm length were adjusted to the participant's upper limb. Laser pointers (Fig. 2) that indicated the position of the humerus head helped the experimenter to position the subject in the device. To familiarize the participant with the ARMin device, a pilot test was performed. After the pilot test, the participant's arm was detached from the device. Then, they were asked to move the arm freely, at their self-selected velocity, with fully extended elbow, in the frontal plane 10 times from 60° arm abduction to 110° arm abduction and back (free movement). In addition to the verbal instruction, the desired movement was also demonstrated by the experimenter. Afterward, participants were asked to remain passive while the experimenter took the subject's arm and repeated the same movement (manually guided movement).

Then, the subject's arm was connected to the ARMin device, and the device moved the arm 10 times from 60 to 110° arm abduction and back in the frontal plane (robot-guided movement). For this movement, the robot was running in active, position control mode. The experimenter selected the velocity close to the self-selected velocity of the free movement. This sequence was repeated four times. Participants of group 1 started with configuration Toff, followed by Ton, Ton and Toff, while participants of group 2 started with Ton, followed by Toff, Toff, and Ton (Table 1).

For the test condition Toff, the angle $\phi = 0°$ and the translational movement of the robot is zero. For the test condition Ton, the angle ϕ is selected based on the test person's body size h_{body} according to Eq. (1). For a test person with $h_{\text{body}} = 1.7\text{m}$ the angle becomes $\phi = 9.1°$, thus moving the arm from 60 to 110° results in a translational movement in the vertical direction $t = r(\cos(60°) - \cos(110°)) = 30.3\text{mm}$.

Table 1 Experimental procedure

Group 1	Robot-guided test-run	Free movement	Manually guided movement	Robot-guided movement Toff	Q1 + 2	Robot-guided movement Ton	Q1-3	Robot-guided movement Ton	Q1-3	Robot-guided movement Toff	Q1-3
Group 2	Robot-guided test-run	Free movement	Manually guided movement	Robot-guided movement Ton	Q1 + 2	Robot-guided movement Toff	Q1-3	Robot-guided movement Toff	Q1-3	Robot-guided movement Ton	Q1-3

Condition Toff stands for movements with $\phi = 0°$ and Ton stands for movements with $\phi > 0°$. In between the movement series, Questions (Q1, Q2, and Q3) were asked to assess the subjective feeling of comfort

After each sequence, three questions (cf. 2.4) to assess how the participant rates the comfort of the previous arm movement were asked. The participants were blinded and did not know which shoulder configuration they were testing. Between each test, the experimenter manipulated the robots' shoulder mechanics. Three manipulations were made: changing configuration Ton to configuration Toff, changing configuration Toff to configuration Ton, and a sham manipulation without changes. The purpose of the sham manipulations was to make the participants believe that something at the shoulder mechanism has changed.

2.4 Questionnaire to assess comfort

After each robot-guided movement sequence, the examiner asked questions to the participants (Table 1). Three questions were asked: Q1: "How comfortable was the movement in the ARMin robot compared to the manually guided movement?" [33, 34] and Q2: "How natural did the motion feel?" [35] on six-point scale with (1 = very bad, 2 = bad, 3 = somewhat bad, 4 = somewhat good, 5 = good, 6 = very good) and question Q3: "How comfortable was the movement in the ARMin robot compared to the previous robot-guided movement?" on a five-point scale (1 = much worse, 2 = worse, 3 = same, 4 = better, 5 = much better). One-tailed paired t test is used to test significance of the differences between the Ton and Toff condition.

2.5 Measurement of the acromion motion

Four active ultrasonic markers where placed at strategic points along the right arm and right shoulder of the participant. The bony markers were selected according to the recommendations of the international shoulder group [31]. Marker 1 at the wrist (ulnar styloid), marker 2 at the elbow (medial epicondyle), marker 3 at the acromion (Angulus Acromialis), and marker 4 at the sternum. During the movements, the position of the markers was recorded with 100 Hz sampling rate using a 3D tracking system (Zebris CMS-HS System). With the elbow fully extended, the arm abduction angle could be calculated out of marker 1 (wrist) and marker 2 (elbow) using the inverse tangent function of vertical distance between the two markers divided by the horizontal distance (in the frontal plane). Then, the relation between the positions of the acromion (marker 3) and the arm abduction angle was analyzed. For each direction of the Cartesian frame (cf. Fig. 1), the second order polynomial function that fits the data in a least squares sense has been calculated. Then, the functions describing the acromion motion were used to calculate the amplitude of the movement in the three Cartesian directions. One-tailed

paired t test is used to test significance of the differences between the Ton and Toff condition.

3 Results

3.1 Questionnaire

The test persons rated the comfort of the ARMin motion in configuration Toff ($\phi = 0°$) compared to the manually guided motion (question 1) with an average and standard deviation 4.11 ± 1.25 out of 6 points. In configuration Ton, the same numbers were 4.19 ± 1.61. Seven participants rated the comfort of configuration Ton higher than Toff, nine participants rated both the same, and four participants rated the comfort in configuration Toff higher than in Ton. The p value for the difference of the means is $p = 0.31$. The naturalness (question 2) was rated with an average and standard deviation 4.35 ± 1.00 for configuration Toff and 4.45 ± 1.09 for configuration Ton. Six participants rated the naturalness of Toff higher than Ton, 10 participants rated both the same, and four participants rated the naturalness of Ton higher than Toff. The corresponding p value is $p = 0.24$.

The responses to the comparative question 3 were When operating mode Ton follows Toff, 14 participants stated that Ton feels more comfortable, six participants felt the same. When the order is inversed, thus when Toff follows Ton, 10 participants stated that Toff feels more comfortable, and 10 felt the same. When Toff follows Toff, six participants stated that the later Toff movement feels better than Toff (after a sham manipulation), and four stated that it feels worse. When Ton follows Ton, three participants stated that it felt better, three stated that if feels the same, and four stated that it feels worse. The average responses with the standard deviations are represented in Fig. 3.

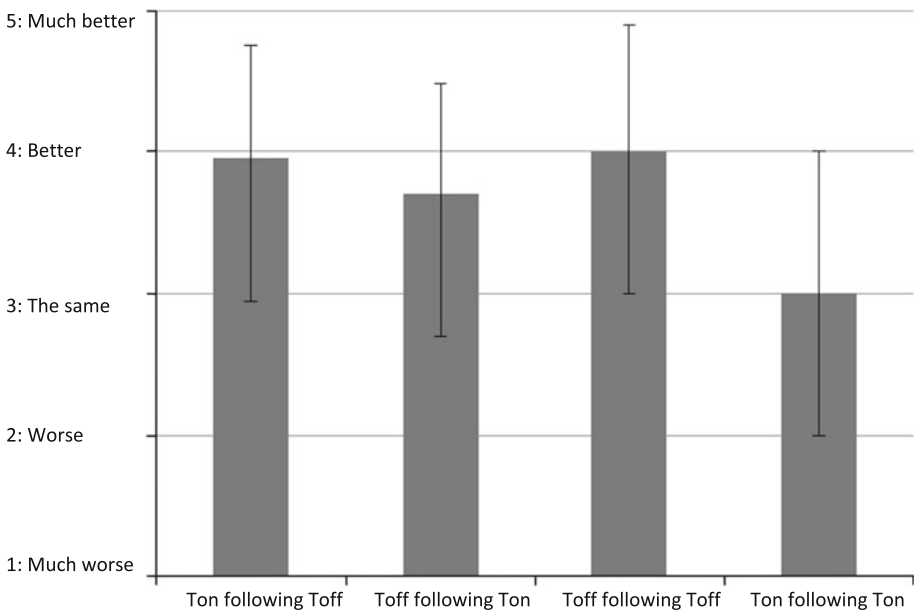

Fig. 3 Responses to the question 3: "How comfortable was the movement in the ARMin robot compared to the previous robot-guided movement?"

4 Acromion motion

The motion of the acromion was analyzed for each test situation: configuration Toff, configuration Ton, free movement, and guided movement. To determine the amplitude, the second order approximations were used to calculate the difference between the value at 60 and 110° abduction angle. Table 2 shows the mean values of all 20 participants. The mean value of the amplitude of the acromion motion in free movement condition is 37.9 ± 8.6 mm, during the guided movement 32.9 ± 9.6mm, 16.2 ± 7.2 mm for configuration Ton, and 15.1 ± 7.1 mm for configuration Toff (Table 2). One-tailed paired t test reveals $p = 0.012$ for the difference of Ton and Toff.

5 Discussion and conclusion

The ARMin III shoulder actuation (in configuration Ton) imposes translational movement (in the vertical y-direction, Figure 1) of the humerus head. As an important feature, the shoulder actuation is symmetric and it can be very easily transformed from left-to-right arm use. Also, the mechanical design is—when compared to other shoulder actuation principles, that is, the ARMin II [27] or the MGA-Exoskeleton [12]—relatively easy to implement and very suitable for commercialization. In this study, we

Table 2 Amplitude of the relative acromion movement during arm abduction from 60 to 110° (in the frontal plane)

	Configuration Toff			Configuration Ton			Free movement			Guided movement		
	x	y	z	x	y	z	x	y	z	X	y	z
Mean value (mm)	−10.2	8.9	−2.2	−11.0	9.5	−3.4	−19.3	29.9	−10.1	−17.2	23.9	−13.3
STD (mm)	5.8	5.2	5.3	5.2	4.8	6.4	4.4	7.9	7.8	4.1	8.4	7.0
	Amplitude			Amplitude			Amplitude			Amplitude		
Mean value (mm)	15.1			16.2			37.9			32.9		
STD (mm)	7.1			7.2			8.6			9.6		

The values are represented in the fixed Cartesian frame with $\vec{x}$ perpendicular to the frontal plane and with $\vec{z}$ pointing in the direction of the gravitational vector $\vec{g}$ (cf. Fig. 1)

tested if it is also more comfortable and natural than a ball-and-socket-type shoulder actuation.

The movement of the acromion (in the coordinate frame introduced in Fig. 1) in configuration Ton is larger than in configuration Toff. The difference is small (1.1 mm), but statistically significant ($p = 0.012$). Hence, configuration Ton is closer [20] to the natural motion than configuration Toff. This suggests that the motion in configuration Ton should feel more natural than in configuration Toff and supports hypothesis 2. The amplitude of the acromion during free and guided motion is factor 2.3, resp. 2.0 bigger than during motion in configuration Ton. Thus, the motion data confirms hypothesis 2, with a small, but significant effect size.

Test persons rated in the questionnaires the comfort and naturalness of Ton and Toff almost the same. Both values were a slightly higher for the configuration Ton, but this difference is not significant. This suggests that the test persons could not feel the difference between the two configurations, which explains the large standard deviation and contradicting statements as shown in Fig. 3. To summarize, the responses of the questionnaires cannot judge hypothesis 1 and 2. Note that indications about the validity and the accuracy of the questionnaire responses can be drawn from the ability to distinguish the repeated tests on Ton or Toff conditions, masked by a sham manipulation. In Fig. 3, most participants judged Toff following Toff as better, which is not consistent. One possible explanation might be that participants were not sensitive enough to feel differences between Toff and Ton.

Given the small difference in the movement of the acromion, one must conclude that when selecting the angle ϕ according to eq. [1] and within the arm abduction range of motion 60 to 110°, the shoulder actuation of the ARMin III device is not more comfortable or natural than a ball-and-socket-type shoulder actuation and hypotheses 1 and 2 must be rejected. It could be that the findings would be different if tested over a larger range of motion. Also, these findings cannot be directly transformed to other robotic devices with shoulder actuations that provide translational movements [10, 12, 16, 24], because they have other mechanical designs.

One of the strengths of this study is that two different shoulder configurations were tested in the same robotic device, thus, ensuring the same seating, the same cuffs, the same movement, and the same positioning of the test person. The positioning of the test person in the robotic device was highly reproducible because of the laser pointer that indicated the position the humerus head.

It could be criticized that movements with larger range of motion should have been tested to reveal more significant differences. This might be true, but the selected range of motion corresponds to the predominant range where the ARMin training occurs [36]. One open question is whether the angle ϕ has been correctly selected. The Eq. (1) is derived in [20, 32] based on the observation of the scapula-humerus rhythm and observations of motion in the gleno-humeral, the acromioclavicular and the sternoclavicular joints [29, 37–39]. This angular data are then combined with CT-data to get the initial position and the individual segment lengths [20, 32]. From a biomechanical point of view, the angle ϕ is correctly described by Eq. (1). But from a practical and experimental point of view, it would be interesting to test also larger angles ϕ to investigate whether this would further improve the comfort and the naturalness of configuration Ton in comparison with configuration Toff.

Limitations of this study are that the study has been conducted with young healthy volunteers while therapy robots are mainly being used in older stroke patients. We chose healthy young adults because they have a better proprioception than older stroke patients [40, 41]. It is clear that there are differences between the shoulder of healthy subjects and stroke patients [42]. Therefore, as a next step, it would be interesting to conduct a similar study with stroke subjects. Another limitation is that questionnaires are rather subjective and a weak tool. Also, the sensitivity and specificity of the questionnaire to detect differences between Ton and Toff are unknown, and we therefore cannot exclude that the lack of differences found is related to the questionnaire design. To get more objective data, it

would be recommended for future studies to include static measurements of the interaction torques. Another limitation is that the study does not check how an end-effector shoulder actuation would compare.

In future studies, it would be very interesting to conduct similar evaluations of other shoulder actuations mechanisms to directly compare the comfort of different shoulder actuation principles. Also, the comparison of the exoskeleton mechanisms with an end-effector-based shoulder actuation would be interesting.

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