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The Impact of an Underactuated Arm Exoskeleton on Wrist and Elbow Kinematics During Prioritized Activities of Daily Living

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Abstract

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This study addresses the feasibility of underactuated arm exoskeletons as an alternative solution to the often bulky and heavy exoskeletons which actuate the shoulder with 3 DoF. Specifically, the study investigates how the wrist and elbow joint adapts their kinematics when the shoulder abduction is constrained. Ten healthy participants conducted three different grasping activities of daily living, during natural motion and during constrained shoulder abduction at two fixed angles: 15 the resting position angle and at an angle of 10 ° abduction from the resting position. Motion capture data was collected and used as input for a musculoskeletal computer model adapted to this study. Statistical parametric mapping tools were employed to analyze the joint angles estimated by the model. The results show significant differences within the joint angles when the shoulder abduction is constrained. The wrist flexion angle deviated up to 13.6 ° and the elbow 20 pronation angle decreased by 8.7 ° on average throughout the movement compared to the natural motion during restricted shoulder abduction motion. Thus, the shoulder could be underactuated and the participants could still accomplish the activities of daily living with changes in the wrist and elbow joint kinematic angles.

Keywords: Exoskeleton, Motion analysis, Kinematics

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1. Introduction

When rehabilitating individuals affected by tetraplegia, the intention is to achieve the maximum possible daily independence. This is provided by human assistance and, to an increased degree, by providing technical devices that help to complete this goal [1]. Thus, the medical community aims to provide new solutions for the disabled individuals, such as exoskeletons to raise their autonomy. It has been shown that medical devices can restore some autonomy to individuals with tetraplegia [2]. Soon, medical devices such as the exoskeleton that is being developed by EXOTIC will be ready to improve activities of daily living (ADL) for high level spinal cord injured individuals, for example through tongue control [3, 4, 5]. Exoskeletons intended for rehabilitation and for more able-bodied users are already on the market [6, 7], and are expected to quadruple the market size in 2025 [8]. In order to empower individuals affected by tetraplegia, several studies have focused on developing upper limb exoskeletons. Gopura et al. [9] reviewed more than 20 upper limb exoskeleton systems. In review, the studies that developed exoskeletons to actuate the 7 degrees of freedom (DoF), comparable to the number of DoFs of the human arm, led to designs that were not mobile [10, 11, 12]. Gupta et al. [13] stated in their study that developing a lightweight exoskeleton system is one of the main challenges. One way to achieve this is to reduce the number of DoFs of the upper limb exoskeleton. For example, Martinez et al. [14] aimed at an exoskeleton with 5 DoF. The purpose of their study was to investigate the optimal 5 DoF to reach the largest workspace and concluded that the 3 DoF of the shoulder and the 2 DoF of the elbow were optimal for the needs of their exoskeleton. Other studies addressed the possibility of reducing DoFs of their respective exoskeletons, as the resulting device was lighter and more efficient. For instance, Wang et al. [15] concluded that a 3 DoF upper limb exoskeleton had the same workspace as one that covered 5 DoFs. In this way, it was possible to reduce the DoF and still meet the objective of the exoskeleton. As the overall goal of assistive exoskeletons is to restore the ability to perform ADLs to users, mimicking the kinematics of the human motion during the ADLs is important for the exoskeletons' purpose. However, exoskeletons with reduced DoFs may not reproduce exactly the same kinematics that the user would perform during their own natural movement. Therefore, analysis of the kinematics induced by an underactuated exoskeleton is important.

Therefore, the hypotheses of this study are:

- Underactuation of the shoulder joint induces changes in the kinematics of the elbow and wrist joints while performing the prioritized ADLs.
- Underactuation of the shoulder joint allows for the performance of prioritized ADLs

To study this, we adopted the tasks prioritized by users with tetraplegia [16]. A detailed kinematic analysis of these ADLs with and without wearing a 3D printed version of the EXOTIC exoskeleton was performed [17]. Kinematic data were extracted from the innate human motions of able-bodied participants performing the selected ADLs and analyzed with the use of a biomechanical model. In summary, this experimental and modelling study analyses the possibility of underactuating the shoulder joint and, further, how this affects the kinematics of the wrist and elbow during the three

selected ADLs. Thus, the study provides a prove of concept on the feasibility of reducing the size of an upper limb exoskeleton by decreasing the number of DoFs of the arm.

2. Materials and Methods

85 This study has three main parts:

1. Analysis of the kinematics of the shoulder, elbow and wrist DoFs during the following three ADLs: drinking from a straw, pouring water and eating a chocolate bar (Fig. 1).
2. Analysis of the kinematics of the three described ADLs with the shoulder abduction DoF constrained and their resulting wrist and elbow motions.
- 90 3. Estimation of the range of motion angles of the shoulder abduction, elbow and wrist DoFs.

Parts 1 and 2 are performed on data from an experiment with 10 able-bodied participants. Part 3 is performed by using the measurements from parts 1 and 2 as input for a musculoskeletal model.

2.1. Participants

95 The experimental data was collected following the ethical guidelines of The North Denmark Region Committee on Health Research Ethics. Ten able-bodied individuals were recruited to perform the experiments. All participants were tested using the handedness test [18] to identify their dominant hand. They all proved to be right-handed, additional information can be seen in Table 1.

100 2.2. Data acquisition

Kinematics were obtained with an infrared motion capture system (Qualisys AB, Gothenburg, Sweden) with 8 IR video cameras (Oqus 300 series) and 100 Hz sampling rate. The cameras were calibrated according to the Qualisys manual. The cameras captured the position of the markers attached to the participants' skin. These were attached following the standard protocol described in the repository of the AnyBody Modeling System by a trained person, Fig. 2. Additionally, two other markers were glued on the table and on the left hand (Fig. 1). These two markers were used to define the beginning and end of the movement cycle, to ensure the reproducibility of the experiment.

2.3. Experimental procedure

110 The experiments were performed in a single one-hour session for each experimental participant. The session was divided into nine parts (3 ADLs and for each of them 3 exoskeleton configurations) in which the volunteer was sitting on a chair with a 90-degree angle between the trunk and the lower limb (Fig. 1). The participant was asked not to lean forward while performing the ADLs. The distance between the trunk and the table was defined as the anatomical length of the hand plus the forearm of each participant. The participant's sternum marker was centered in

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the middle of the defined spots for the object (Fig. 1) The starting position for all tasks was with the palms resting on the ipsilateral knee. Then, volunteers were asked to complete the tasks 8 times. This amount of repetitions was selected due to the fact that during experimental validation the participants were found to lose their focus after the eighth repetition.

120 The ADLs for the experiment were described as:

1. Reach the marker on the table (left hand)
2. Reach and grasp the object (glass, bottle, or chocolate bar) with which the task was involved (right hand)
3. Conduct the action of drinking, pouring or eating (right hand)
- 125 4. Bring the object back to the table (right hand)
5. Bring the right hand back to the initial position
6. Bring the left hand back to the initial position

Three configurations were considered:

- (1) Natural motion without constraint (FM)
- 130 (2) Constraint: resting position angle (FR)
- (3) Constraint: angle of 10 ° abduction from the resting position (FO)

The glass with the straw, the bottle or the chocolate bar were placed on the table at marked spots (Fig. 1). The straw was placed pointing towards the participant and the chocolate bar in the transversal orientation. A data recording was started at the beginning of each sequence when the participant did not move and stopped at the end when the 8 repetitions were completed. All data was captured for analysis at a later time. Afterwards, the participant was equipped with the upper arm part of an early 3D printed exoskeleton prototype from the EXOTIC exoskeleton group [3] (Fig. 1). This exoskeleton allowed free movement of the right upper extremity, but prevents shoulder abduction. This joint was fixed at the resting position, defined as the angle of shoulder abduction when the participant was in the described initial position, during the entire set of tasks (Fig. 1). Then, the volunteers were asked to repeat the proposed ADLs 8 times. Next, the exoskeleton was fixed in the configuration which adds 10° of shoulder abduction to the resting position, the participant repeated the tasks 8 times.

145 2.4. Biomechanical model

AnyBody 7.1 is a software for modelling and simulating human movement. This software describes every segment of the musculoskeletal system as a rigid body. The pose of each rigid body is defined by six degrees of freedom: three translations and three rotations. The motions of the segments are constrained by joints with other segments or with the environment. Additionally, to drive the movement of our model the motions of the markers recorded during the experiment were included to complete the equations that describe the kinematics of the model. The developed model is an adaptation of the available Full-body Gait Simple model [19]. It was modified to fulfill the purpose of this study as follows. It consisted of 6 segments: head, thorax,

155 right humerus, right radius, right ulna and right hand. The distal end of the thorax with the head was fixed, thus no translations of any coordinates were allowed. On the contrary, all 3 rotations were left free, similarly to what is the case when a subject sits on a chair. The other segments were linked to the thorax with the anatomical joints defined in the Full-body Gait Simple model. A description of the model can be found in Table II.

2.5. Data processing

160 The motion capture data registered during the experiments was post-processed as follows:

1. Gap filling: Some of the markers were not seen by the cameras during the recording. Therefore, their location was calculated using the Qualisys relational method, which estimates the position of the missing marker by knowing the position of three other markers in the same segment, assuming a rigid body.

165 2. Video cutting: The videos contained 8 repetitions of a task performed by a participant. The recording was cut from the frame where the hand started moving to the last frame of the repetition when the hand returned to its initial position.

Motion capture data was loaded in the AnyBody model. The model assigned the position of the markers, thus the bony landmarks of the participants, to the virtual markers described in the AnyBody Full-body Gait Simple model. Every segment defined in the musculoskeletal human model was scaled according to the real distance between the markers, the height and weight of every participant. This process was performed for all subjects and movements. After scaling, kinematics and inverse dynamics were computed. The kinematic analysis provides the motion of the body segments without considering the forces. It calculates the position, velocity and acceleration of the involved segments and joints.

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2.6. Data analysis

The joint angles of the shoulder, elbow and wrist joints were extracted from the simulated results. The duration of the individual trials was normalized from 0% to 100% of the motion cycle. Then, the signals were subdivided into 201 intervals. Within these intervals the mean and standard deviations for the samples within each condition and ADL were calculated for all the subjects and trials, Fig. 3, 4 and 6. To statistically compare the inferred parameters over the percentage of the cycle, one-dimensional Statistical Parametric Mapping (SPM) techniques were implemented in order to analyze a time-series signal along the samples [20]. The SPM1D Matlab tool [21] was used to assess the normality of the data. When they were normally distributed, the ANOVA equivalent test was carried out, followed by a post hoc analysis when ANOVA revealed statistically significant differences (SSD) between the different conditions. A Bonferroni-corrected paired t-test was used to evaluate the differences between each pair of condition.

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3. Results

The SPM1D normality test found normality in the data along all three configurations for the joint angles during the conduction of the ADLs, except for a few intervals where it was trending

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towards being normally distributed. Thus, the data was assumed to be distributed normally. Hence, the equivalent one-way repeated measures ANOVA from the SPM1D toolbox was performed to compare the joint parameters during the ADLs, under the following three conditions: FM, FR and FO. Only SSD intervals of the wrist and elbow kinematics were reported.

195 *3.1. Shoulder abduction angles*

The shoulder abduction angle was plotted during all the conditions. The modifications of the FM angle are in accordance to the exoskeleton's restrictions (Fig. 3). The SPM1D ANOVA found SSD in the shoulder abduction angle during the tasks "drinking from the straw" and "pouring water form a bottle". These tasks were found to show SSD since the shoulder abduction during FM differs from the constrained conditions (Fig. 3). Moreover, the intervals in which no statistical significance was found were at the beginning and end of the cycle where the hand starts to move and returns to the initial position. In these intervals the shoulder abduction does not present SSDs, as FM is found between FR and FO. This, added to the fact that the SDs are considerable, it resulted in the absence of SSDs in these small intervals. No SSD was found during the task "eating a chocolate bar" due to the similarity between the FM and the FO angles. However, the results are consistent with the shoulder abduction restrictions that were introduced in all configurations.

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3.2. Wrist flexion angles

During the FM condition, the wrist flexion angle was smaller than during the FR and FO conditions throughout all the ADLs (Fig. 4). The results suggest that when the exoskeleton was mounted on the human arm, the participants conducted the ADLs with more wrist flexion. Furthermore, a larger overall wrist flexion is observed during the ADL of "eating a chocolate bar" for the FO setup. However, ANOVA only showed SSD significant differences along the intervals underlined in blue (Fig. 4). These wrist angle modifications are specially relevant during the task "eating a chocolate bar". Finally, the post hoc analysis showed no SSD between the FR and FO configurations (Fig. 5). Therefore, restricting the shoulder abduction movement with an exoskeleton leads to more wrist flexion on the "pouring water from a bottle" and "eating a chocolate bar" tasks an average of 10.8 ° and 11.3 ° for the FR and FO setups respectively compared to the FM configuration throughout the SSD intervals, (Fig. 5).

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3.3. Wrist abduction angles

Wrist abduction angles did not differ significantly, except for an average of 3.8 % of the cycle (mean of the 3 ADLs) within the intervals when retracting the hand to perform the tasks.

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3.4. Elbow pronation

The shoulder abduction angles along the FR configuration during the task "drinking from a straw" were very similar to those obtained during FM. This is consistent with the differences reported in the elbow pronation angles because the differences are also very similar in this ADL between the FR and FM configuration, as illustrated in Fig. 6. The FO configuration has a mean elbow pronation angle along the whole cycle 8.7° lower than for FM condition and 9.3° lower than

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the FR condition. In the same way that occurs in the shoulder abduction angles for this ADL, but with an opposite sign.

230 The post hoc analysis showed SSD between FM-FO and FR-FO, along the underlined intervals (Fig. 7). Therefore, during tasks where the shoulder abduction is held at a certain angle throughout the ADL during FM, such as "drinking from the straw", fixing the shoulder abduction at a certain angle, for instance 10° to the rest position (FO), inversely affects the elbow pronation angle.

4. Discussion

235 Studies suggest that exoskeletons attempting to actuate the 7 DoF, in which the human arm is normally described, led to non-mobile designs [10, 11, 12]. Aiming to design a very light and mobile assistive exoskeleton, the study proposes to reduce 1 DoF of the shoulder to perform the tasks of "drinking from a straw", "pouring water from a bottle" and "eating a chocolate bar". Such as Martinez et al. [14] and Wang et al. [15] propose in their respective studies, designs of
240 exoskeletons with reduced DoF are feasible to comply with ADLs or to obtain a desired workspace. Furthermore, the results of this study support that the design of an exoskeleton with underactuation of the shoulder is adequate to perform the ADLs described in this study. Additionally, it shows that the reduction of the shoulder abduction DoF has an impact on the wrist and elbow joint kinematics.

245 These findings are especially relevant when designing an exoskeleton with the aim to assist individuals affected with tetraplegia. Because the upper limb exoskeleton must support all the motion of the arm to conduct the desired tasks. Therefore, an electronic control specifying the rotations of the exoskeleton joints is needed to perform the tasks. The results of this kinematic study show that when the shoulder abduction DoF is restricted, some kinematics adaptations
250 along the wrist and elbow joints were required to successfully conduct the ADLs as innate human thinking would suggest. Hence, it provides design parameters that could be used to design the actuation of rotations of the exoskeleton joint. Thus, if no difference are observed between the restricted and the free movement, the study provides hints for controlling the exoskeleton in the described ADLs. Otherwise, if the task cannot be performed by the exoskeleton's DoFs, there are
255 infinite kinematic combinations to complete the task. Then, this study aims to shed light with alternative kinematics offered by healthy experimental subjects that are expected to bring the user as close as possible to their natural movements.

4.1. Shoulder underactuation

A 3D printed prototype of the upper part of the EXOTIC's arm exoskeleton was used to restrict
260 the shoulder abduction of the healthy participants at two different abduction angles, the resting position angle, and an angle with 10° offset from the resting position. Fig. 3 indeed shows a constant mean angle difference of approximately 10° between the FR and FO configurations, in the active part of the movement. This is what we expected of an effective restriction. However, it can be noticed in the results that at the beginning and at the end of the movement, when the
265 participants released the weight of their own arm, FO approaches to FR. The reason for this is

probably that it is difficult to restrict completely shoulder abduction due to both soft tissue deformation and a non-perfect fit. This suggests that the exoskeleton's intended restrictions seemed to work as expected on the active part of the movement.

4.2. Kinematic adjustment

270 This study describes ADLs where the wrist and elbow joints significantly adjusted their kinematics to complete the tasks due to the restriction of the shoulder abduction. These SSDs are relevant since they can amount to a mean difference of 13.6°, in the maximum interval in the "pouring water from a bottle" task between FM and FR. Additionally, there were cases when the wrist joint angle changed its configuration from flexed to extended (Fig. 5), meaning that the wrist joint performed an antagonistic motion as an effect of the restricted shoulder abduction. For instance, as reported in the results section, during the "eating chocolate bar" ADL, the wrist joint adapted from an extension in the FM condition to a flexion in the FR and FO conditions during the first SSD interval.

4.3. Sizing an upper limb exoskeleton for the ADLs described

280 In this study, 2 exoskeleton configurations and 3 ADLs were considered. The shoulder abduction angle in which the shoulder joint was fixed affected the performance of the 3 ADLs differently. For instance, assuming the hypothesis that the closer to the FM condition the better will be the user's experience when performing it, with respect to the task "drinking from a straw", the FR configuration did not differ from the FM configuration, with respect to the elbow pronation angle. Whereas the results from the FO configuration differed from the FM configuration in almost the entire cycle (Fig. 7).

On the other hand, the FO configuration would be more suitable than FR for the ADL "pouring water from the bottle". The mean differences within the SSD intervals of the wrist flexion angle were 1.8° closer for the FO configuration to the FM configuration than in the case of FR (Fig. 5).

290 Finally, the kinematics results presented in this study can have an impact on the positioning of the actuators or on the direction of the rotation of the motor since the wrist adaptation can evoke to an antagonistic motion, as described above.

4.4. Other variables that may influence the results

295 Finger movements were not captured by the motion capture camera, and therefore different grasping techniques may have affected the wrist joint angles. The AnyBody musculoskeletal model assumes the segments described as rigid bodies whereas the markers were placed on the skin (and thus soft tissues). Additionally, the centers of rotation of the joints were calculated according to the position of the markers on the bony landmarks, thus the joint rotation centers were calculated based in these estimations.

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5. Conclusion

The aim of the study was to investigate whether the underactuation of the shoulder joint of an exoskeleton allows for the performance of prioritized ADLs and whether underactuation of the shoulder joint induces changes in the kinematics of the elbow and wrist joints while performing the prioritized ADLs. The results of the study showed that despite the restrictions applied on the exoskeleton shoulder, the participants were still able to perform prioritized ADLs. Further, the results showed that the shoulder abduction restriction had an impact on the kinematics of the shoulder, elbow and wrist motion during the selected ADLs. This impact resulted in wrist flexion angle deviation of up to 13.6° compared to the natural motion. Furthermore, during one ADL (eating a chocolate bar) the wrist motion adapted from an extension in the FM condition to a flexion in the FR and FO conditions during the first SSD interval. The FO configuration resulted in modifications in the elbow joint, as the pronation angle was on mean 8.7° lower than for the FM configuration during the entire motion. These differences should be considered in the design of an exoskeleton as they can lead to antagonistic movements. Finally, it has been shown that the angle at which the shoulder joint is fixed is important in the kinematics of the task to be performed.

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Table 1: Participants features

Gender	Height (m)	Weight (kg)	Age (y)
male	1.74	65	28
male	1.81	74	24
male	1.85	76	24
female	1.64	57	21
male	1.85	85	29
male	1.85	80	31
male	1.89	92	28
male	1.87	80	21
female	1.67	54	21
male	1.8	92	24
Mean & SD	1.79 (± 0.09)	75.5 (± 13.3)	25.1 (± 3.7)

Table II: Model Description

Joint	Parent	Child	DoF	Coordinates
Neck	Thorax	Head	3	Rotation XYZ
Chair-Thorax	Chair	Thorax	3	Rotation XYZ
Shoulder	Thorax	Humerus	3	Shoulder flexion Shoulder abduction Shoulder rotation
Elbow	Humerus	Forearm	1	Elbow flexion
Radio-Ulna	Ulna	Radius	1	Pro-supination
Wrist	Ulna	Hand	2	Wrist flexion Wrist abduction