Abstract

In case of tetraplegic patients, restoration of the gripping function has been subject to major restrictions so far. Both operative interventions, such as tendon or muscle transfer as well as technical aids like neuroprostheses require an actively controllable shoulder function for the hand to be placed freely in space. Patients suffering from paraplegia with a complete loss of arm movements, who need help all day long, would win a considerable degree of independence and quality of life by a simple gripping function already. The “OrthoJacket” project is therefore aimed at creating the necessary technical and clinical prerequisites. By combining an actively moved orthosis with functional electrical stimulation (FES), a non-invasive, modular hybrid orthosis shall be developed for the upper extremity. Requirements for using a hybrid elbow and shoulder joint orthosis shall be presented below.

1 Introduction

In Germany, 50,000 to 60,000 people are suffering from paraplegia, with this number rising annually by another 1800 patients due to accidents and increasingly due to diseases of the spinal marrow [1]. Apart from paraplegic patients, a considerable number of neurological patients suffer from paralysis of their upper extremity and limitations of their independence and quality of life following a stroke or craniocerebral trauma. Loss of motoric functions and in particular of the gripping function leads to life-long dependence on helping persons and means a considerable restriction of the quality of life. The paramount objective of modern rehabilitation medicine is to at least partly restore the individual functional defects. According to the current state of the art, functional electrical stimulation (FES) represents a major option for functional improvement, if surgical options are lacking [2,3]. All FES systems for restoring the gripping function may only be used successfully, if the shoulder and elbow are functioning correctly, which holds for patients with a damage of the spinal marrow below the 5th cervical vertebra. The reason is that systems presently available may only improve the gripping function proper, such that patients have to possess sufficient residual functions to place the hand independently in space. So far, only few working groups studied the problem of restoring the function of the elbow and shoulder: [4] used an extended free-hand system to restore the typically lacking elbow straightening of sub-C5 paralyzed patients. In contrast to this, [5] used a system with intramuscular, percutaneous electrodes to restore the shoulder function in hemiplegic and tetraplegic patients. Both systems are exclusive FES systems, i.e. suitable muscle groups are stimulated not only for generating motion, but also for maintaining a static joint position. Due to the weight of the upper extremity and non-physiological, synchronous activation of nerve endings when applying external electric pulses, rapid muscle fatigue occurs, which largely limits the principle usability of such systems in routine clinical use.

Today, an early, target-oriented, function-specific training of high intensity is performed to restore the function to a certain extent by enhancing neuroplasticity on the spinal and supraspinal levels. First approaches exist to applying this intensive movement training also with the help of training machines [6,7]. Their use, however, is limited to the hospital due to their size and complexity. A simple, but still effective training device for the upper extremity, which may also be used at home, does not yet exist.

2 Methods

2.1 Calculation of the elbow flexion forces required

To dimension and position an actuator element for the additive movement of the elbow joint, gravity must be considered. The lower arm has a share of 1.7% and the hand 0.7% in the total body mass (m). Hereinafter, the total body mass shall be assumed to be 80 kg. To hold a lower arm with a force of Fg of 19.2 N in a position against gravity, an actuator has to apply a force
$F_z$ that is dependent on $L_2$, on $L_3$, and on the flexion angle according to the equation (see Fig. 1):

$$F_z = \frac{F_g \cdot L_1 \cdot \sqrt{L_2^2 + L_3^2 - 2 \cdot L_2 \cdot L_3 \cdot \cos \beta}}{L_2 \cdot L_3}$$

Assuming lever lengths of $L_1 = 16$ cm, $L_2 = 5$ cm, and $L_3 = 20$ cm, the following tension forces were calculated for compliance with the equilibrium condition at the elbow joint at 3 different joint positions:

<table>
<thead>
<tr>
<th>Elbow flexion angle</th>
<th>Force $F_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$150^\circ$</td>
<td>75.5 N</td>
</tr>
<tr>
<td>$90^\circ$</td>
<td>63.3 N</td>
</tr>
<tr>
<td>$30^\circ$</td>
<td>48.8 N</td>
</tr>
</tbody>
</table>

Table 1: Required forces for stabilization

Consequently, an actuator that is supposed to hold the elbow joint against gravity must generate at least 75 N, if no own force can be applied by the patient. Holding the full arm against gravity much higher forces are needed at the shoulder joint. Presuming the mass of the full arm with $F_g = 40$N the resulting holding force $F_z$ for stabilization of the shoulder is in the range of 100 to 250N, depending on the lever of the actuator.

2.2 Stimulation experiments

In order to measure the range of motion caused by FES the corresponding muscles for elbow flexion, and shoulder abduction and anteversion were stimulated using the muscle stimulation device “Motionstim8” made by Krauth & Timmermann.

For activation of elbow flexion electrodes were arranged at a distance of about 2 cm directly above the muscle belly of m. biceps brachii. Flexion of the elbow took place with a current of 14 mA, a pulse width of 250 µs, and a frequency of 25 Hz. For measurement of an anteversion movement of the shoulder the active stimulation electrode was placed at the pars clavicularis of the deltoid muscle approx. one cm below the acromion process and the indifferent electrode at the proximal end of the humerus at the deltoid muscle. To evaluate shoulder abduction (which is mainly performed by the pars acromialis of the deltoid muscle), the electrodes were placed at the head of the humerus with a distance of 1 cm to each other. The stimulation current for measurements at the shoulder was 18 mA. To minimize fatigue effects, a pause of 8 seconds was made after every stimulation phase of 15 seconds. The flexion angle was measured in the unloaded state and with additional weights of 360 and 1000 g in the hand of the healthy test persons. The degree of motion was determined videooptically using skin markers.

3 Results

Image analysis yielded the following results (Fig. 2):

<table>
<thead>
<tr>
<th>Additional weight</th>
<th>Elbow flexion</th>
<th>Shoulder anteversion</th>
<th>Shoulder abduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 gr.</td>
<td>$101^\circ$</td>
<td>$70^\circ$</td>
<td>$41^\circ$</td>
</tr>
<tr>
<td>360 gr.</td>
<td>$86^\circ$</td>
<td>$50^\circ$</td>
<td>$41^\circ$</td>
</tr>
<tr>
<td>1000 gr.</td>
<td>$46^\circ$</td>
<td>$29^\circ$</td>
<td>$26^\circ$</td>
</tr>
</tbody>
</table>

Table 2: Joint motion by FES with and without additional loads.

4 Discussion

It was demonstrated by the experiments that only limited degrees of motion can be achieved by functional electrostimulation even under ideal conditions in case of an additional load. Hence, an additional external force is necessary that supports the movements of the upper limb against gravity so that the patient can exe-
cute activities of daily living (ADL) by applying part of the forces and torques required to move the joints himself [8]. Lightweight and flexible fluidic actuators like the pneumatic McKibben artificial muscle that shortens with increasing pressure can be used which may apply the above forces [9-11] (see design study depicted in Fig. 3). Miniature components for fluid control have already been developed [12]. However, further measurements remain to be performed to determine the extent to which these motions may be transferred to tetraplegic patients with a residual function of the corresponding muscles.

![Design study of the elbow-supporting element of “OrthoJacket”](image)

**Fig. 3:** Design study of the elbow-supporting element of “OrthoJacket”.

## 5 Conclusion

In analogy to designs for the lower extremity [13,14], an approach is being developed to combining an FES system with a mechanical orthosis. A passive, but blockable orthosis stabilizes the elbow joint. The torques generated or to be held are much smaller than those required by the knee joint when standing or walking. Hence, restoration of the elbow function appears to be possible with the hybrid system.

## 6 Acknowledgement

The authors gratefully acknowledge the valuable help of Dr.-Ing. Rüdiger Rupp of the Orthopedic University Hospital, Heidelberg, Germany.

## 7 Literature