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Mechanical System for the Rehabilitation of Human Hand Function

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***Abstract*— The hands are used to perform very different activities, and to carry out necessary daily needs. Due to their exposed location and frequent use, hands have a high risk of injury. Permanent damage is not limited to physical performance, but can also have psychological effects on the patient. Therefore, the fullest possible rehabilitation of the hand is desirable. Only a very limited number of therapeutically necessary movement tasks can be taken on nowadays using the current technical systems for hand rehabilitation. Motivated by these facts, a new system is conceived: each joint of the finger can be separate moved by fluid-driven. The system can measure forces, the number of movements and other data for each joint. In this paper, the conception of the mechanotherapy system will be limited to one finger.**

***Keywords*— mechanotherapy system, rehabilitation of the hand, compliant membrane, fluidical actuator**

I. Introduction

“It is by having hands that man is the most intelligent of animals.” [1] This quote from Greek philosopher Anaxagoras found in Aristotle's work De partibus animalium demonstrates early recognition of the hand's prominent and central role within human life.

Precisely because the hand is such a versatile and highly accurate tool, even minor functional deficits of the hand can significantly compromise a person's independence and quality of life, in addition to having a negative impact on his or her social environment. Furthermore, the frequent use of the hand compared to other body parts creates an increased risk of injury and one-third of all injuries and accidents involve the human hand [2].

Doctors, occupational therapists and physical therapists have devised a broad range of treatment options for the rehabilitation or preservation of hand function after injury or illness. An important component is the exercise and loading of the injured or diseased muscles, tendons and joints, also known as mechanotherapy. Current systems implement treatment methods which have been commonly available since the mid-20th century. The corresponding technological conditions only permit the movement of the entire finger. The new system will allow the targeted movement of individual finger joints, opening up a new range of therapy variations.

II. Anatomical Basics

The skeleton of the hand consists of 27 bones in addition to smaller sesamoid bones. The hand is divided into several sections, as shown in figure 1. The bones of the metacarpus (1) are attached to the carpus and the phalanges are in turn attached to the metacarpal bones. The fingers are either three-boned digits (index finger to little finger) or two-boned digits (thumb). All fingers contain proximal (2) and distal (4) phalanges and the three-boned digits also contain a medial phalanx (3). The individual bones are connected by joints marked by lines II through V in subfigure 1(a). Subfigure 1(b) describes the hand's spatial planes and the possible directions of motion ([3] and [4]).

Each digit is connected to the metacarpus by a corresponding metacarpophalangeal joint (see subfigure 1(a), II). This joint allows abduction (or spreading), adduction (or bringing together), extension (or stretching) and flexion (or bending). In contrast, the proximal interphalangeal (or PIP) joint and the distal interphalangeal (or DIP) joint only allow extension and flexion. Therefore, the development of the mechanotherapy system only involves the application of extension and flexion.

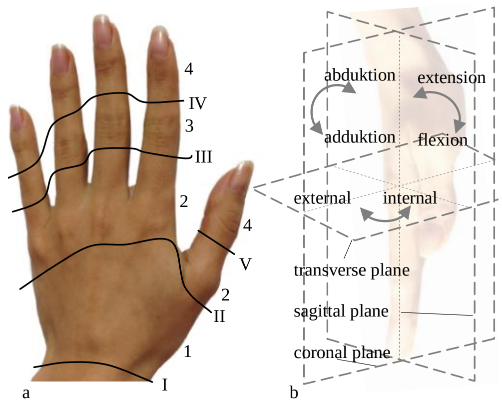

Fig. 1 Anatomical fundamentals of the hand: division of the hand and terms for motion of the hand with respect to the motion planes and directions

III. Specification of System Scope

The system introduced here (which is the subject of a future design) is intended to facilitate intensive mechanotherapy of the hand as part of after-accident rehabilitation or for the correction of neurological dysfunction (e.g. after a stroke) and chronic disease (e.g. disorders on the rheumatic spectrum). The goal is to enable patients to return to working life quickly and efficiently or at least reach a physical state in which they can, with physical assistance, participate in society and achieve personal fulfilment.

There are numerous technical resources available to rehabilitate and treat hand disorders. However, they are neither multifunctional nor portable and they do not permit the separated focussed treatment of individual hand joints. From a technical point of view, the existing systems can be divided into three groups: rigid body systems, compliant systems [5] and hybrid systems [6]. Rigid body systems are robust and allow the exact positioning of the hinge joints as well as adapting to the length of the fingers. They are also capable of generating large amounts of force. A disadvantage is the increased amount of space required between the digits. In contrast compliant systems require less available space and are lightweight. However, they usually do not allow for length adjustment, exact positioning of the hinge joints or transmission of smaller forces. Hybrid systems can, depending on their structure, profit from the advantages of both rigid body and compliant systems. Therefore, the system depicted here will be implemented as a hybrid system.

The system is expected to transmit large forces up to 80 N, exhibit a large range of motion, allow the individual motion of each finger joint, all using a relatively compact design. Moreover, the new system should be modularly adaptable to a patient's height and therapeutic needs (the affected joint can be moved in a directed way, fully blocked or provided with resistance). A mechanotherapeutic system with these characteristics is not yet available but such a system could significantly and positively impact the course of rehabilitation therapy. This system should contain an actuator as well as resistance and locking elements for each finger joint, to be selectively activated as needed. The actuator would allow the joint to be moved passively. The resistance element provides a reasonable force to be overcome during independent movement, similar to a dynamic orthosis. The locking element fixes the corresponding joint at a specific angle.

IV. Motion Transmission Gear

The system requires a mechanism to transmit force or momentum of an actuator to the finger joint. In addition to transmitting force and momentum, the mechanism needs to convert the displacement of a translatory drive into a rotation ([7]). The transmission of force should be implemented through gear components and joints. When selecting a mechanism, it is important to assure that only torque is exerted about the axis of the finger joint while horizontal and vertical forces are prevented, as these would inhibit the desired motion, which in turn could lead to injury of the finger joint.

In order to avoid unwanted forces on the finger joint, the axis of the finger joint must be aligned with the axis of the corresponding mechanotherapeutic system joint. This can be accomplished by placing the joints of the mechanotherapeutic system to the side of the finger joint. Figure 2 illustrates the design of the mechanism to convert the actuator stroke into a rotation of the finger joint.

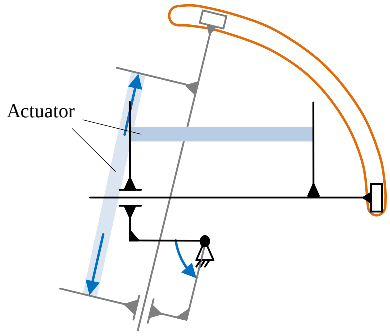

Fig. 2 Gear mechanism for converting the actuator stroke into rotation of finger joint

For this, the relative stroke path was placed in such a way that the transmission of the force F within the slider-pivot joint always uses a constant moment arm h (Fig. 3).

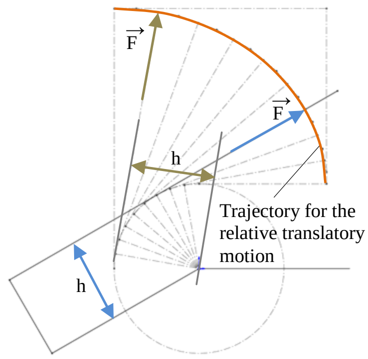

Fig. 3 Determination of a path for the relative translatory motion in the gear mechanism

Additionally, it is important to consider that the proximal phalanges are not immediately accessible because of the connection to the metacarpus. A cam gear avoids this problem by allowing motion along a circular path, the virtual axis of which is identical to that of the finger joint. Figure 4 shows the implementation of this solution within the complete mechanism, including actuators. The rigid frame design facilitates the mounting of actuators and sensors; additionally, it is possible to integrate a length adjustment for different hand sizes. Cushioning inside the finger frame can be designed to allow the individual adaptation to different hand shapes (such as finger diameter, deformations etc.).

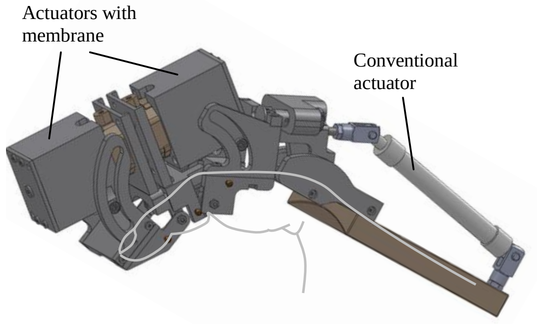

Fig. 4 Hand therapy system with Actuators

V. ACTUATORS AND SENSORS

Fluidically driven compliant actuators allow high flexibility in the setting and changing of mechanical parameters, providing increased comfort for users (compact set-up, flexibility). The actuators consist of a guided cylinder connected by a membrane, which simultaneously serves as a seal and as a buffer to allow the actuator to provide an increasing cyclical force (figure 5).

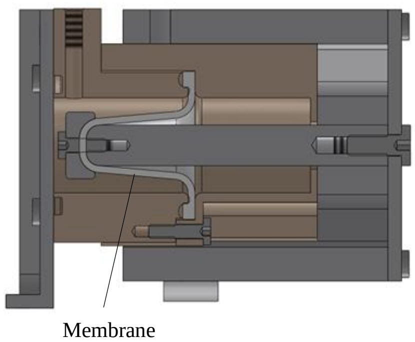

Fig. 5 Actuator design

Figure 6 shows a model of the highly elastic membrane. The spring creates resistance within the joint; thus, the spring rate can be used to simulate various types of stress representing different diseases.

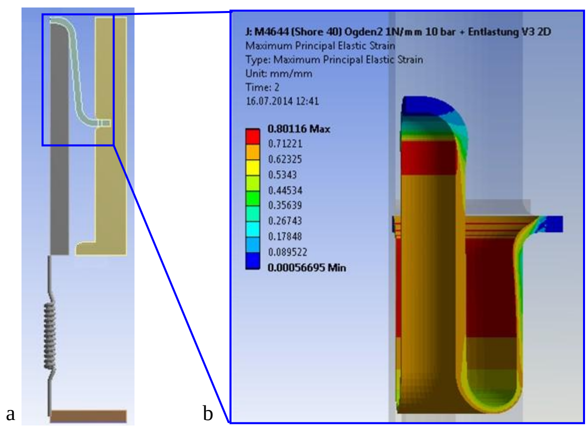

Fig. 6 Modelling of the actuator subsystem with membrane using an FE model: (a) representation of the subsystem to be modelled, (b) FE model of the membrane

Figure 7 demonstrates the force to be transferred by the membrane; here, the spring rate is assumed to be 10 N/mm. A pressure of 10 bar allows the transfer of over 80 N of force.

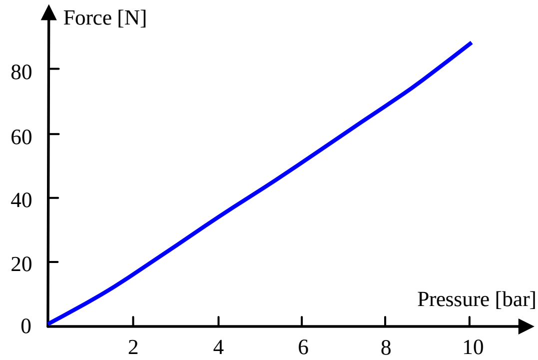

Fig. 7 Force generated by the actuator as a function of applied pressure assuming a spring rate of 10 N/mm

These actuators can be replaced by passive elements, which can dampen or block active movements from the user.

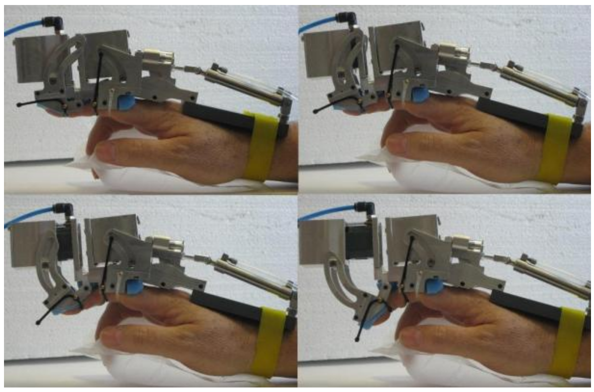

Fig. 8 Motion of the proximal interphalangeal joint

Figures 8 and 9 show the mechanotherapy system in use, with movement of the proximal and distal interphalangeal joints, respectively. For each joint a maximum rotation angle of 70° is possible.

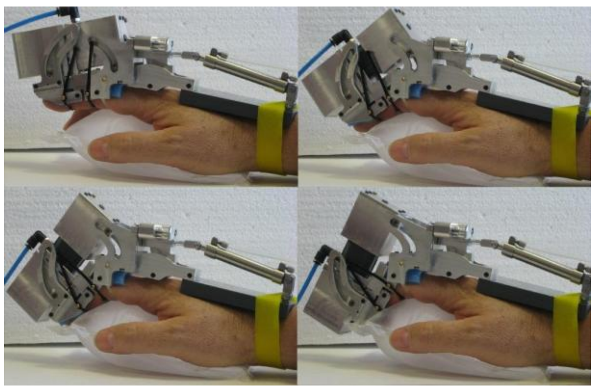

Fig. 9 Motion of the distal interphalangeal joint

The integrated sensors in connection with the data acquisition, storage and analysis services provided by the microcontroller make it possible to record the functional state of the hand and to validate the therapeutic measures being carried out. This data collection can be used to record and document the rehabilitation and therapy process using objective criteria. Using this gathered data, therapy can be constantly adapted to attain optimal success in healing. Parameters to be determined include achieved motion range and forces applied as well as changes over the course of therapy. The generated parameters can be sent to a PDA or PC using an appropriate interface for archiving, which yields significant time-planning advantages for doctors and patients.

Bringing in signals from surface electromyography into the actuator control loop can open up completely new possibilities for therapy: the patient's lower arm is outfitted with surface electrodes (in a sensor cuff) to measure the myoelectrical action potentials, which are analysed by a real-time signal processing unit to determine patient-initiated hand and finger movements and transform these movements into actuator signals for functional or force assistance. The resulting control signals are incorporated into the control loop of the fluidically driven actuators. Through this, the patient is able to perform targeted finger movements for active, specific training even if the functional motion is limited.

VI. Conclusion

This article introduced a mechanotherapy system for the rehabilitation of hand function in the medical space. In particular, the work concentrates on the development of the design fundamentals of a multifunctional system for hand mechanotherapy. The goal is to develop and test new therapy approaches stemming from qualitatively new functions which go beyond current methods. The developed system stands out from the existing mechanotherapy systems due to the increased variety of functionality. It can be used both for passive hand movement and as a dynamic orthosis, the mechanical parameters of which can be individually adapted during a treatment session. Integration of sensors makes way for objective therapy evaluation.

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