Evaluation of Hand Grasping by Instrumented Glove

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Abstract, - In this paper the evaluation of effectivenes of instrumented glove in measurement of hand opening and preshaping during reach-to-grasp movement is described. In the experiment presented in this work the reach-to-grasp movement of one healthy subject was measured by two different types of motion-tracking devices (3D optical system, Optotrak, and commercial instrumented glove, 14 sensors Ultra Data Glove) with the aim to answer if the rather simple glove-system can substitute complex and expensive optical system in assessment of hand preshaping during reach-to-grasp.

Key-Words, - hand kinematics, reach-to-grasp movements, hand preshaping, hand model, instrumented glove, rehabilitation

1 Introduction

The prehension can be defined as the application of functionally effective forces by the hand to an object for a task, given numerous constraints. The study of grasping can be divided into three areas of research, reaching to grasp an object [1-3], exerting force on the object [4, 5], and dexterity of the fingers while manipulating the object [6, 7]. Some of the researchers from the Laboratory of Robotics and Biomedical Engineering, Faculty of Electrical Engineering, University of Ljubljana, have oriented their investigations toward each aspect of grasping. Kurillo [8, 9] focused his research on the assessment and rehabilitation of hand function by using computerized measurements of force exerted by the hand in virtual reality. Veber [10] has analyzed the dexterity of the fingers while changing the orientation of the grasped object.

The scope of this article is the assessment and evaluation of the reaching phase of grasping by using computerized measurements of hand and fingers kinematics in healthy population [11-13]. On the kinematic level, prehension involves the orienting and posturing of the hand and fingers, with the appropriate transportation of the limb to the correct location in space [14]. When a person reaches out to grasp an object, the hand opens into some suitable shape for grasping and manipulation – suitable, in the sense that the person's understanding of the task influences the shape of the hand [14].

In [13] we defined new parameters which represent the preshape of fingers during prehensile movement. So far, the grasping configuration of the hand was described by the aperture, the term defining the distance between the tips of thumb and index finger. The drawback of such representation is that the most of grasping techniques which include all five fingers are observed only through the behavior of the thumb and index finger while the influence of other fingers is ignored. New parameters overcame this drawback by including all fingers involved into grasping. We proposed the fingers pentagon, the planar shape obtained by interconnecting the neighbouring fingertips. The surface area of the pentagon (denoted as PSA) is the quantitative measure of the hand opening, while the spatial angle between pentagon and hand normal describes the orientation of the fingers with the respect to the dorsum of the hand i.e. the fingers preshaping during reaching movement [13].

The study of human movements has always been closely linked to that of motion analysis technology, from the first qualitative descriptions of object grasping using photography by Napier [15], through the use of video motion capturing systems which use TV cameras [16, 17], to the present day computerized motion analysis technologies which are used to study an increasing number of kinematic parameters, allowing the detailed description of joint trajectories in three-dimensional space. Some of these highly precise but expensive systems are Vicon, Optotrak, Elite, etc. Many researchers nowdays also use inertial sensors for measurement of different body movements [18, 19]. Recently, there are intentions of using hand gloves equipped by motion sensors for capturing hand and fingers movements. But, studies which would investigate the efficacy and accuracy of instrumented gloves are still lacking.

In this article we have compared the simultaneous measurements of prehensile movements by two commercial motion-capture systems, optical system Optotrak and instrumented glove which provides goniometric data of the hand joints. In pioneering studies with instrumented gloves, Santello and Soechting [2, 20, 21] employed a glove with bend-resistant sensors that allows the measurement and capture of the metacarpal and proximal interphalangeal joint angles of the hand. This information was then used to assess the evolution of hand configuration in a quantitative fashion. The results of their glove-based measurements showed that during reaching movements directed to objects with different shapes, the fingers move in a way to gradually preshape the entire hand and to approximate the object contours as the hand approaches the object [2].

Schettino [22] used the instrumented glove in measurements of hand preshaping to observe both the coordination deficits in the performance of a naturally complex movement and the effects of Parkinson's disease on internally-guided motor control. The results of their study indicate that relative to controls, Parkinson's disease patients exhibit various coordination deficits including a delayed specification of hand preshaping and a delayed time to peak aperture.

Instrumented gloves can be used in telemanipulation where a robot is directly controlled by a human user. Turner [23] has done the experiment where the user, wearing the sensorized glove, interacts with a virtual world through a virtual human hand. User hand motions, described by glove readings, are mapped into robot hand motions, allowing the user to remotely perform a task.

The study which would simultaneously employ both 3D optical motion-capture system and instrumented glove has not been conducted so far. The research, which compares both systems, will be included in our study with the aim to give the answer if the expensive and complicate-to-use optical motion-capture systems can be substituted by inexpensive gloves in the evaluation of hand preshaping and fingers opening. We have proposed the hand model which could be efficiently used for calculation of fingers joints spatial positions by using direct kinematic approach and joint angles measured by commercial instrumented glove. Joint spatial positions can then be used as input data for calculation of prehension parameters proposed in [13].

By using the proposed hand model and data measured by glove, we have calculated prehension parameters and compared them with parameters calculated from Optotrak data. It is expected that the comparison of measurements performed on healthy subject will answer the question whether the instrumented glove can be implemented as an efficient tool for assessment of parameters of reaching-to-grasp movement and is it possible to develop the method for the evaluation of hand function during the approaching phase of grasping based on rather inexpensive and simple system which uses instrumented glove.

2 Methods

One healthy, right-handed male subject participated in the study, wearing the Data Glove and eight Optotrak markers attached to the hand. Five markers were attached to the fingertips, and three were on the dorsum of the hand, attached above the thin glove fabric, for the calculation of the hand coordinate system. Both Optotrak and Data Glove measured the hand movement at a sampling frequency of 60 Hz. Subject was asked to reach and grasp two different objects, a block (width=12cm, height=6cm, length=20cm) and a cylinder (diameter=6cm, height=12cm), Fig 1.

Block was initially positioned in horizontal (denoted as test 1) and vertical (test 2) orientation, at d = 25 cm distance from the initially positioned hand, Fig 1. Cylinder was placed in two initial positions, at the distance of d = 25 cm (test 3) and d = 35 cm (test 4), in front of the hand, Fig 1.

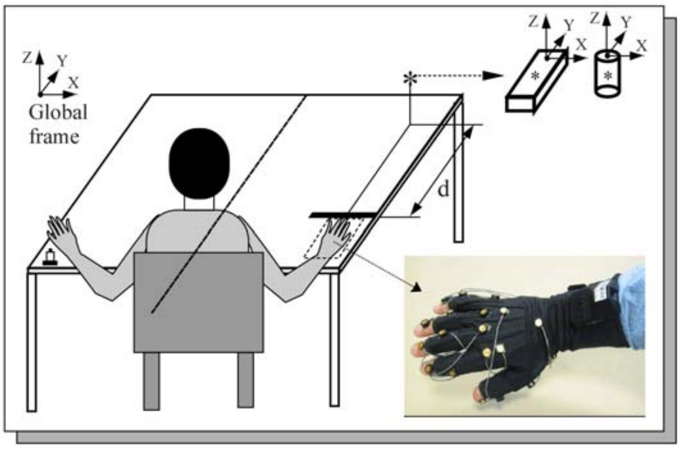

Fig 1. *Experimental setup, subject and objects initial poses (* signifies the object center of gravity)*

The experimental procedure (Fig 2) always started with the experimenter placing the object into the initial pose. Subject, when ready, pressed a push button. Upon receiving the "push-button" signal, computer PC1 sends the synchronization ("start acquisition") signal to the computer PC2, and the simultaneous data acquisition by Optotrak and Data Glove starts. Three seconds later, an audio signal informed the subject to commence with grasping. Subject reaches for the object and, upon grasping it, puts it at the centre of the table. Optotrak and Data Glove stopped the acquisition after six seconds and experimenter moves the object back into the initial position.

The procedure continued until five trials of grasping the objects in both two poses were recorded. There were all together $5*(2_{block}+2_{cylinder})=20$ recordings. The reach-to-grasp movement started with lifting of the palm from the table and finished with a stable object grasp.

The movement onset was determined as the first change of the capitate marker position since we have always observed that this marker starts moving before the others do. The end of the movement was determined with the moment when the vertical and horizontal positions of all finger markers stabilized for a while, prior to a new change caused by lifting the object and placing it on to the table. The endpoint of the movement was further determined by observing the point where the interfinger distance stopped decreasing [1].

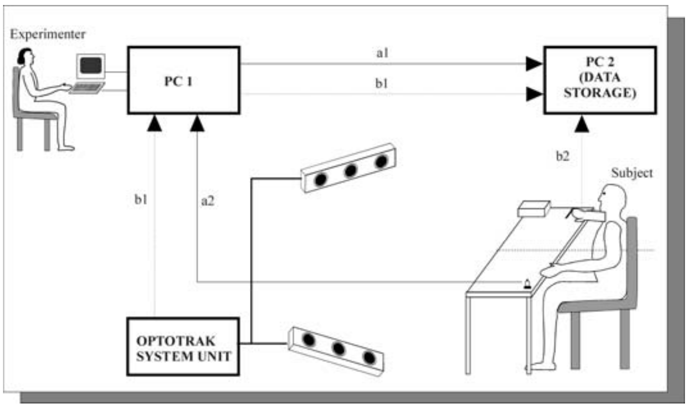

Fig 2. *Block scheme of the experimental set-up. After the subject presses the pushbutton, both Optotrak and Data Glove simultaneously start to collect data. Three seconds later the subject, informed by an audio signal, starts the reaching movement. [**a1**, synchronization ("start acquisition") signal; **a2**, pushbutton signal; **b1**, Optotrak data; **b2**, Glove data]*

The time normalization of all the assessed data was performed. The marker trajectories were plotted against the percentage of the movement duration. The hand coordinate frame was defined using markers positioned at the dorsum of the hand, Fig 1. The frame origin was defined by the marker, which was positioned at the center of the capitate bone.

The **x** axis points from the origin to the middle point between MCP2 and MCP4 markers. The **z** axis is perpendicular to the plane defined by the three dorsum markers making the **y** axis a cross-product of the axes **z** and **x**.

2.1 Glove Calibration and Hand model

The instrumented glove used in this study, the 5DT Data Glove 14 Ultra, is designed and commercialized by Fifth Dimension Technologies (5DT), Inc. [24]. It is equipped with 14 optic-fiber bend-sensors measuring flexion of metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints of index to little fingers (carpometacarpal (CMC) and interphalangeal (IP) joints in case of thumb finger), and relative abduction angles between all adjacent fingers. To convert digital output into an angular format (in degrees), each of glove sensor has to be calibrated. We proposed the technique which applies polinomial fitting. The calibration procedure is shown in Fig. 3. Hand movements were simultaneously measured by 5DT Data Glove 14 Ultra and Optotrak motion tracking system, Fig 3.

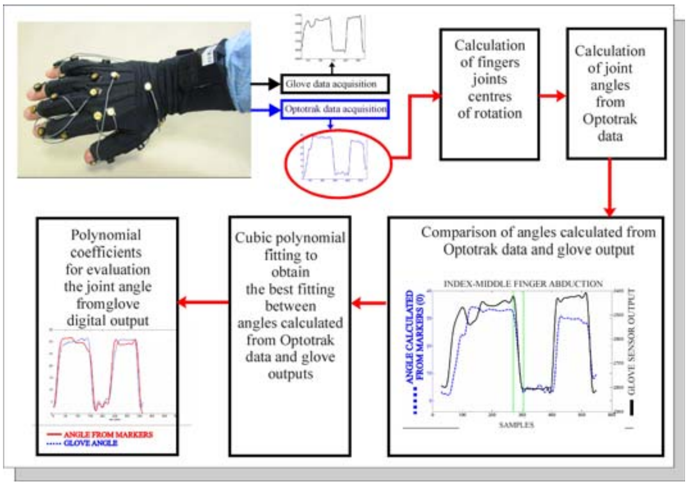

Fig 3. *Data Glove calibration procedure*

A set of subsequent measurements were performed on a single, healthy, right-handed male subject. Subject was asked to position his hand, palm down, parallel to the horizontal plane, wrist in neutral position. This posture corresponds to zero flexion, zero extension, and zero abduction of the most of hand joints. Subject was instructed to perform a set of different hand movements, in each one particular finger joint was fully extended or abducted. Nineteen Optotrak markers were positioned on the hand, one on the capitate bone, additional two on the dorsum of the hand, twelve on MCP, PIP, and DIP joints of the II-V digits, and four on CMC, MCP, IP and tip of the thumb. Firstly, data measured by Optotrak were processed in a way that we calculated fingers joints centres of rotation from surface markers [12]. Then we calculated joint angles from positions of joints obtained in the preceding step. By comparing the angles calculated from Optotrak data and glove digital outputs, and by applying cubic polynomial fitting to obtain the best fitting between angles calculated from Optotrak and glove, we obtained polynomial coefficients for evaluation the joint angle from glove digital output, Fig 3. In order to obtain fingertip spatial positions from glove data, an adequate hand model has to be used. There are different hand models used for various applications [25, 26]. In our approach, the hand is modelled by a 20 degrees of freedom skeleton, whose location is given by the wrist middle point and whose orientation is given by the orientation of the frame attached to the wrist. Some degrees of freedom, DOFs, are reduced in order to obtain the model simple enough, but to respect human capabilities and span of motion. Each finger has 4 degrees of freedom. Fingers index to little have one DOF in abduction/adduction and three in flexion/extension. Thumb has two DOFs in CMC joint which describe thumb circumduction and two DOFs in flexion/extension. The hand skeleton model is shown in Fig 4.

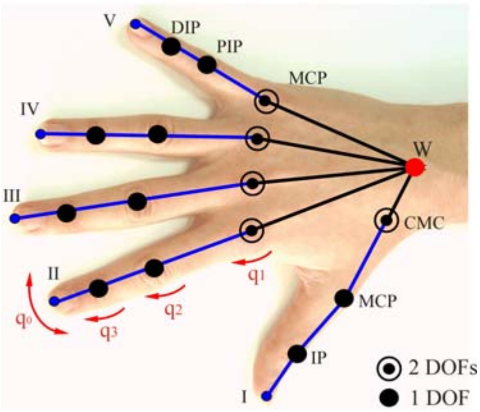

Fig 4. *Hand skeleton model*

Fig 5 shows the kinematic model of the hand and coordinate systems attached to each joint. Fingers index to little are modeled in the same way, as shown in Fig 6. Absolute abduction angle q_0 is calculated from the relative abd. angle measured by glove, Fig 5. Flexion angles q_1 and q_2 are directly measured, while the angle in DIP joint, q_3 is physiologically coupled to q_2 by the following expression, $q_3=2/3q_2$. Angles α_{IN}, α_{RI}, and α_{LI} which define the MCP positions of index, ring, and little finger, respectively, have fixed values, since the position of MCP joints is determined by hand anatomy. Hand segments lengths, l_i, were collected by Buchholz [27].

Six reference frames will be used for representing the kinematics of these four fingers, Figures 5 and 6, $\{W\} = [W, \mathbf{x_w}, \mathbf{y_w}, \mathbf{z_w}]$ (the hand reference frame), $\{F_0\} = [MCP, \mathbf{x_0}, \mathbf{y_0}, \mathbf{z_0}]$ (the finger plane reference frame), frames $\{F_1\}=[MCP, \mathbf{x_1}, \mathbf{y_1}, \mathbf{z_1}]$, $\{F_2\}=[PIP, \mathbf{x_2}, \mathbf{y_2}, \mathbf{z_2}]$, and $\{F_3\}=[DIP, \mathbf{x_3}, \mathbf{y_3}, \mathbf{z_3}]$ are attached to MCP, PIP and DIP joints. Frame $\{F_4\}=[TIP, \mathbf{x_4}, \mathbf{y_4}, \mathbf{z_4}]$ is the finger final frame attached to the fingertip.

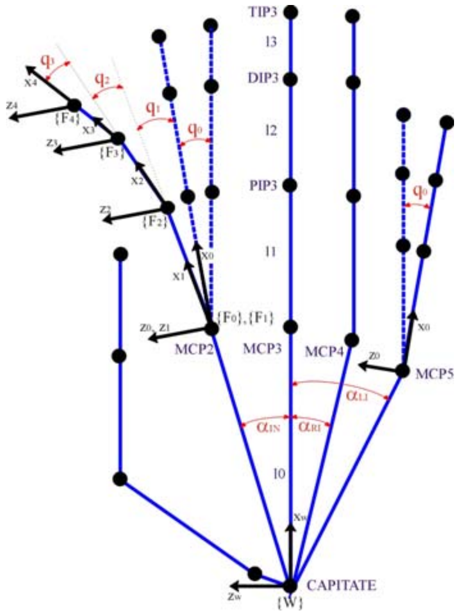

Fig 5. *Kinematic model of the hand; top view*

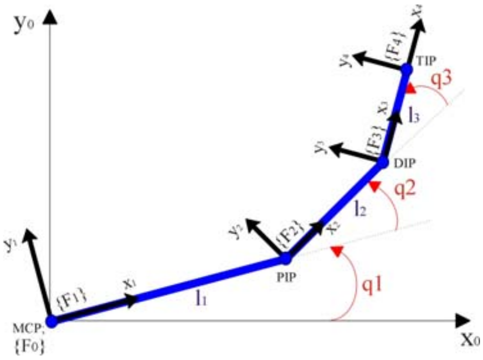

Fig 6. *Kinematic model of the of the index, middle, ring, and little finger; view in the plane of motion*

By applying the direct kinematics, we calculated the positions of fingertip and finger joints with respect to the hand reference frame {W}. We defined homogeneous transformation matrices as follows [28]:

- The frame $\{F_0\}$ is rotated relative to frame {W} about $\mathbf{y_w}$ by q_0, and translated by $l_0\cos\alpha$ in $\mathbf{x_w}$ and $-l_0\sin\alpha$ in $\mathbf{z_w}$ direction, Fig 5. The description of frame $\{F_0\}$ relative to {W} is,

$$ {}^{W}_{F_0}\mathbf{T} = \begin{bmatrix} \cos q_0 & 0 & \sin q_0 & l_0 \cos\alpha \\ 0 & 1 & 0 & 0 \\ -\sin q_0 & 0 & \cos q_0 & -l_0 \sin\alpha \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Note, in case of index finger α has negative value.

- The frame $\{F_1\}$ is rotated relative to frame $\{F_0\}$ about $\mathbf{z_0}$ by q_1, Figures 5 and 6. The description of frame $\{F_1\}$ relative to $\{F_0\}$ is,

$$ {}^{F_0}_{F_1}\mathbf{T} = \begin{bmatrix} \cos q_1 & -\sin q_1 & 0 & 0 \\ \sin q_1 & \cos q_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

- The frame $\{F_2\}$ is rotated relative to frame $\{F_1\}$ about $\mathbf{z_1}$ by q_2, and translated by l_1 in $\mathbf{x_1}$ direction, Figures 5 and 6. The description of frame $\{F_2\}$ relative to $\{F_1\}$ is,

$$ {}^{F_1}_{F_2}\mathbf{T} = \begin{bmatrix} \cos q_2 & -\sin q_2 & 0 & l_1 \\ \sin q_2 & \cos q_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

- The frame $\{F_3\}$ is rotated relative to frame $\{F_2\}$ about $\mathbf{z_2}$ by q_3, and translated by l_2 in $\mathbf{x_2}$ direction, Figures 5 and 6. The description of frame $\{F_3\}$ relative to $\{F_2\}$ is,

$$ {}^{F_2}_{F_3}\mathbf{T} = \begin{bmatrix} \cos q_3 & -\sin q_3 & 0 & l_2 \\ \sin q_3 & \cos q_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

- The frame $\{F_4\}$ is translated relative to frame $\{F_3\}$ by l_3 in $\mathbf{x_3}$ direction, Figures 5 and 6. The description of frame $\{F_4\}$ relative to $\{F_3\}$ is,

$$ {}^{F_3}_{F_4}\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & l_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

The joints positions given in the frames attached to the observed joint are notated as,

$$ {}^{F_1}\mathbf{MCP} = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}^T; \quad {}^{F_2}\mathbf{PIP} = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}^T $$
$$ {}^{F_3}\mathbf{DIP} = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}^T; \quad {}^{F_4}\mathbf{TIP} = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}^T $$

The joints positions given in the wrist frame, $\{W\}$, will be calculated as follows,

$$ {}^{W}\mathbf{MCP} = {}^{W}_{F_0}\mathbf{T}\,{}^{F_0}_{F_1}\mathbf{T}\,{}^{F_1}\mathbf{MCP} \tag{1} $$

$$ {}^{W}\mathbf{PIP} = {}^{W}_{F_0}\mathbf{T}\,{}^{F_0}_{F_1}\mathbf{T}\,{}^{F_1}_{F_2}\mathbf{T}\,{}^{F_2}\mathbf{PIP} \tag{2} $$

$$ {}^{W}\mathbf{DIP} = {}^{W}_{F_0}\mathbf{T}\,{}^{F_0}_{F_1}\mathbf{T}\,{}^{F_1}_{F_2}\mathbf{T}\,{}^{F_2}_{F_3}\mathbf{T}\,{}^{F_3}\mathbf{DIP} \tag{3} $$

$$ {}^{W}\mathbf{TIP} = {}^{W}_{F_0}\mathbf{T}\,{}^{F_0}_{F_1}\mathbf{T}\,{}^{F_1}_{F_2}\mathbf{T}\,{}^{F_2}_{F_3}\mathbf{T}\,{}^{F_3}_{F_4}\mathbf{T}\,{}^{F_4}\mathbf{TIP} \tag{4} $$

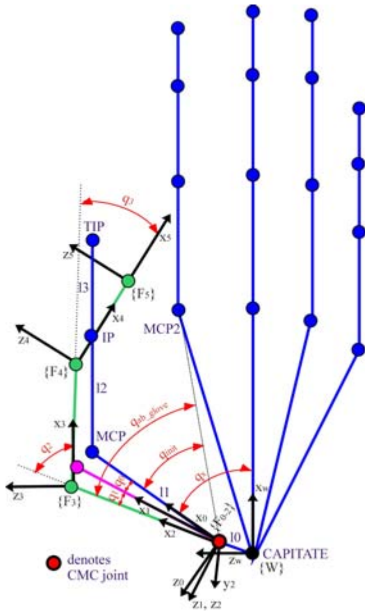

Fig 7. *Kinematic model of the thumb; Top view*

Kinematics of the thumb is more complex comparing to other fingers modeled as planar manipulators, Fig 7. Motion of the thumb is defined by two rotations around **y** and **z** axis in CMC joint (angles q_0 and q_1) followed by two rotations around the **y**-axis, in relative frame description (flexion angles q_2, q_3, directly measured by the glove). The thumb thus points to the little finger knuckle base. Glove measures relative abduction between thumb and index finger, q_{ab_glove}, which is used for the estimation of the CMC angles q_0 and q_1. Angles q_{init} and q_x, used by the model, are fixed and determined by the hand anatomy. More detailed description of the thumb and hand hand model can be found in [11].

Some parameters of hand preshaping introduced in [13], such as pentagon square area (PSA) and angles between pentagon & hand normals were calculated, from the data measured by Optotrak and Data Glove. Results were compared.

3 Results and Discussion

By using data measured by Data Glove and the proposed hand model, we calculated fingers joints spatial positions and presented them in local and global coordinate frame. Figure 8 presents hand skeleton during the whole grasping movement in local coordinate frame, in case of grasping cylinder (test 3). Each other sample is shown.

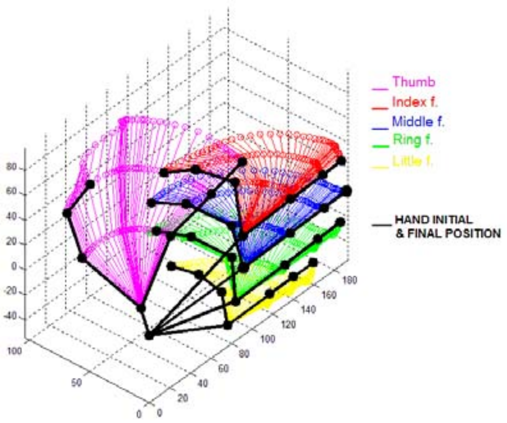

Fig 8. *Hand skeleton during the whole grasping trial*

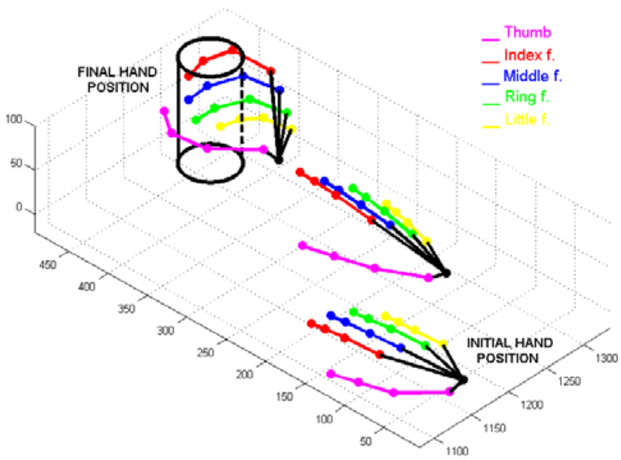

Fig 9. *Hand approaching and grasping cylinder shown in global coordinate system*

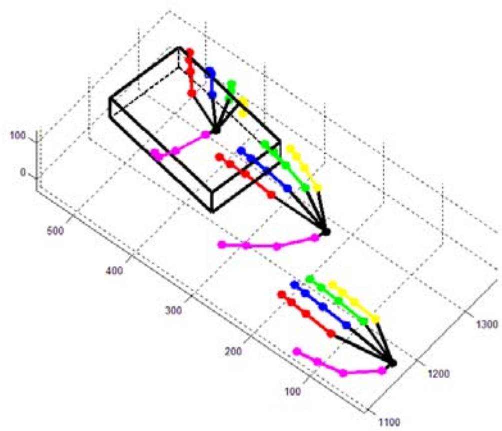

Fig 10. *Hand approaching and grasping block shown in global coordinate system*

Initial and final hand positions are presented by thich black skeleton. In initial position hand is fully extended and adducted (hand lays on the table), while in final position fingers are flexed around cylinder and only slightly abducted. This figure is a good example of fingers gradually preshaped from the initial position into the final grasp.

Figures 9 and 10 show hand skeleton approaching toward and grasping cylinder (test 3) and block (test 1), respectively, in global coordinate frame. Better insight into hand and fingers configuration while grasping the horizontally oriented block is provided by Fig 11 which shows the side and top view of hand skeleton.

Figure 12 shows trajectories of pentagon surface area (PSA) for 2 grasping tests, both for data measured by Optotrak and Data Glove. Figure 13 presents trajectories of angles between hand & pentagon, for 2 grasping tests. Trajectories are averaged over 5 grasping trials. By observing figures 12 and 13, it can be noticed that hand prehension parameters (PSA trajectories and angles between hand & pentagon) calculated from glove data do not deviate significantly from parameters calculated from Optotrak, which proves that the glove can equally efficiently be used as a tool for measuring the parameters of reach-to-grasp movements. One drawback of this glove is that it does not have the sensor for wrist position, so in our calculations and transformations from local (wrist) to global coordinate system we used wrist positions measured by Optotrak. Yet, gloves with wrist position sensors are commercially available as well.

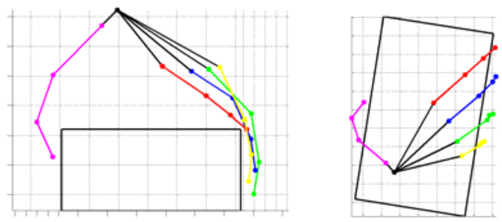

Fig 11. *Side (on left) and top (on right) view of hand model while grasping the block*

4 Conclusion

In conclusion, it can be stressed that hand movement assessment plays a decisive part in determining the extent of impairment and deciding its treatment. The outcomes can, in fact, be used by the surgeon to target the success of a specific operation, whereas the rehabilitation therapist can monitor progresses and focus on the most beneficial treatments.

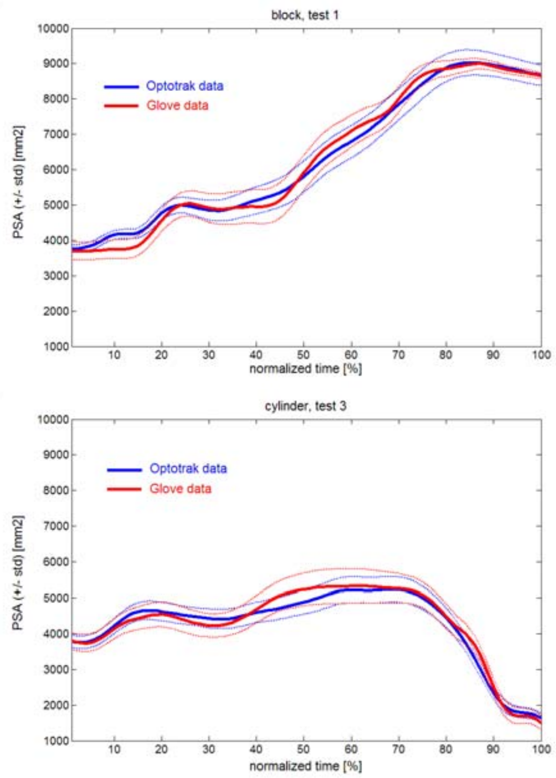

Fig 12. *Trajectories of pentagon square area (PSA) for 2 grasping tests. Comparison between PSA trajectories calculated on the basis of Optotrak and glove data*

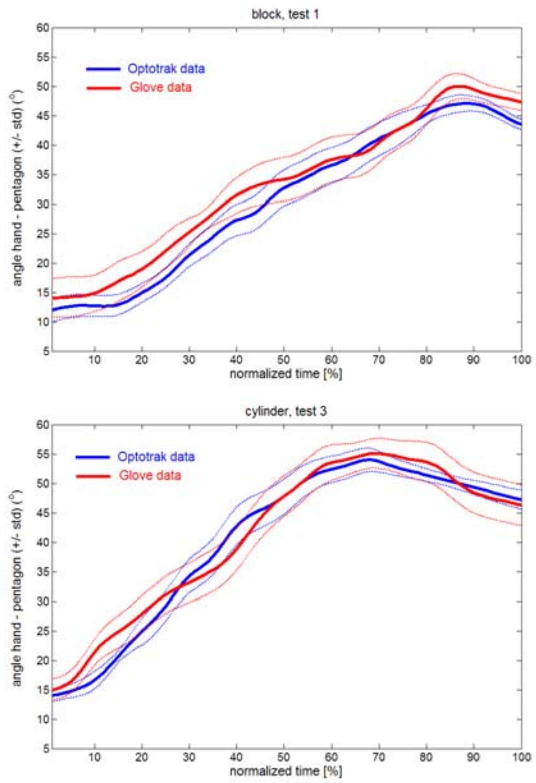

Fig 13. *Trajectories of angle between hand and pentagon normal for 2 grasping tests*

Therefore, an objective assessment of hand function (including reach-to-grasp movement) is important in rehabilitation in order to evaluate the effectiveness of selected therapeutic approach and to provide optimal treatment for a patient, maximize therapy outcome and reduce costs. Our aim was to provide the quantitative description of healthy prehension which could then be used as a comparable standard when dealing with diagnosing of the degree of hand impairment in patients and determining the improvements after the rehabilitation therapy.

We believe that the methods proposed in this article could be helpful in such tasks. In order to use these methods as an efficient tool in assessment of prehensile movements in clinical and rehabilitation environment, it is necessary to implement them in a measuring and therapeutic system which would be simple and inexpensive.

Thinking about such a system which would include low-cost, easy to use, sensorized device for measuring of hand kinematics lead us to the instrumented glove. Since such a glove is relatively new tool in assessment of hand function, some relevant studies dealing with its functionality and accuracy still lack. Therefore, our aim was to examine the efficacy of a commercial data glove in assessment of hand preshaping during grasping. Our study involving measurements of healthy hand prehension, simultaneously done by data glove and highly precise but expensive 3D optical motion capture system, shows that data glove can be used as equally efficient tool for measuring and calculation of hand opening and fingers preshaping during prehensile movements.

Therefore, our suggestion for a future work would be to apply our methods for assessment of reach-to-grasp movements in measurements on patients and to develop and implement a low cost, glove based system for measurements of prehensile movements in rehabilitation environment.

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