Anthropometric measurements for hand rehabilitation robotic devices using video processing

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Abstract. This paper is presenting video processing applications for determining anthropometric measurements used for developing robotic rehabilitation devices. This paper is part of an ongoing project of developing rehabilitation devices aimed for the human hand, mainly for regaining motor functions by the aid of robotics. This paper is presenting research using video processing software for data collecting. The focus of rehabilitation is aimed for the human hand, mainly for regaining motor functions by the aid of robotics. The area of application for the robotic rehabilitation devices are for patients suffering from paretic symptoms following stroke.

1. Introduction
In this paper, an overview is presented regarding applying video processing technology in collecting and processing anthropometric measurements of the human hand. Information generate from the research will aid in developing medical robotics, specifically the data collected is applied and used in a larger project for hand motor function assistance and rehabilitation using robotic devices. [1] [2] Dimensional parameters of the human hand were observed and documented in a comprehensive statistical study using advanced video processing technologies. The purpose of this paper is to establish a good understanding of the human hand anatomy in order to design more ergonomic, compatible and easy to use robotic rehabilitation devices for hand motor function therapy and assistance. Taking into account present day robotic rehabilitation devices mentioned in numerous papers in this filed such as [3] [4] [5], we can say that some of the common issues are regarding the interfacing between the robotic device and the human body, this is due to the variable nature of the biological world. Most of the state of the art robotic rehabilitation devices are rigid, and do not fit perfectly on the human hand due to anthropometric variations in dimensions form one personas hand to the other.

In order to design modular, compliant and customised rehabilitation devices the outer robotic exoskeleton of the device must match the dimension of the patients’ hand. Previous methods of collecting the anthropometric data of each individual involved complex and time consuming procedures done usually manually by specialized personnel. Measurements that often are imprecise and subjected to human error, a need for an automated way of collecting the dimensional data from individuals needing rehabilitation devices are needed. There are a few non conventional technologies that can come in aid in collecting these type of data such as 3D scanning, coordinate measurement machines (CMM) and video processing are just a few of these technologies [6]. In the following paragraphs, research regarding data collecting using video processing is presented.
2. Materials and methodology used

Taking into consideration that a number of factors such as cost, efficiency and training required to implement a measurements solution, the video processing options is by far the most cost effective method since it has the possibility of using commercially available video cameras. Compared to the cost of a 3D scanner or CMM, video processing solutions are a more economical option from a hardware point of view. While special cameras exist that have the ability to generate 3D objects such as the Xbox Kinet camera, in this paper regular general purpose video cameras are used.

Another factor that was taken into consideration when measuring the hand parameters using video processing is the cost of the software, which in many cases can be substantially more that the actually hardware or equipment. Expensive video recognition and processing software can be unobtainable for most clinics and due to the high software cost a 3D scanner may be a better option. [7] [8]

For this research *Kinovea*, a free Open Source licensed software, was used to analyze and collect the needed data. The video camera used for capturing the video was a DSLR Nikon 3200 digital camera. The videos captured were filmed at a resolution of 1920x1080 pixels and 25 frames per second. Adhesive markers were placed in key points on the joint centers of the subjects as seen in figure 1. The dimensions of the markers are used as reference dimension in calibrating the software.

![Figure 1. Key measurement points.](image)

The line maker is used to calibrate the dimension measurement, using a known dimension as a reference the software automatically calculates the dimension between any user defined points. The dot markers are used to track the point position, tracking in done automatically. Data that can be generated by tracking the joint angular movement are: angle value, trajectory, speed and acceleration.

3. Hand kinematics

The human hand being a biomechanical system has an incredibly complex, highly articulated structure with a large number of controllable degrees of freedom (DOFs), which generate dexterous and versatile movements. Due to the nature of the human hand and its numerous DOFs making an accurate model proves to be a difficult and challenging task. As a result numerous simplified models have been used to describe the biomechanical properties of the human hand present in the literature of this area of research. [9] A review and comparison of such models used in literature has been examined by [10] focusing on simplified kinematic models.

For this paper we will consider a kinematic model comprised of 19 links that represent the simplified equivalent of the human bones, and 24 degrees of freedom (DoF) that represent the numerous joints. Links are defined by $a_{ij}$ and joints by $\theta_{ij}$ where $i$ represents the fingers and thumb number, and $j$ refers to its corresponding link or joint number. Direct kinematics is used to obtain the finger tip position and orientation according to the finger joint angles. Model equations are calculated by means of the Denavit-Hartenberg (D-H) parameters [11] [12]. Two different models are needed for describing the kinematics of the human hand, one for the fingers and one for the thumb. In other words, the same kinematic configuration is used for the index, middle, ring and little fingers while for the thumb a slightly different model is used.
notation for the finger links are as following: metacarpal \( (a_{MC}) \), proximal \( (a_{PI}) \), middle \( (a_{MI}) \) and distal \( (a_{DI}) \). Similarly the joints are represented as: carpometacarpal \( (\theta_{CMC}) \), proximal interphalangeal \( (\theta_{PIP}) \) distal interphalangeal \( (\theta_{DIP}) \) and metacarpophalangeal, which is modeled by a universal joint (2 DoF) that can perform abduction/adduction movement \( (\theta_{AMCP,aa}) \) and also flexion/extension \( (\theta_{AMCP,fe}) \) rotations. The thumb is comprised of 4 DoF and is modeled using 3 links: metacarpal \( (a_{TM}) \), proximal \( (a_{TP}) \), and distal \( (a_{TD}) \). The thumb joints are defined as: metacarpophalangeal \( (\theta_{TMCP,fe}) \), interphalangeal \( (\theta_{TIP}) \) and trapeziometacarpal, which is also defined by a universal joint that defines the abduction/adduction \( (\theta_{TMCP,aa}) \) and flexion/extension \( (\theta_{TMC,fe}) \) respectively. The rest of the joints are modeled by revolute joints. [14] Parameter \( d_{i,j} \) is always null since bones are aligned, and parameter \( a_{ij} \) is the angle of separation of the \( Z_{i-1} \) axis and the \( Z_{i} \) axis, measured in a plane perpendicular to the \( X_{i} \) axis, utilizing the rule of the right hand. The direct kinematics of these fingers is shown in equation 1.

\[
P_{i} = \sum_{i} T_{i}(a_{i}) = \sum_{i} T_{i}(\theta_{i}) = \sum_{i} T_{i}(a_{i},\theta_{i}) = \sum_{i} T_{i}(a_{i},\theta_{i},\alpha_{i}) = \sum_{i} T_{i}(\alpha_{i},\beta_{i}) = \sum_{i} T_{i}(\alpha_{i},\beta_{i},\gamma_{i})
\]

Where terms in equation 1 are:
- \( p_{i} \) represents a matrix that contains position and orientation of the i-finger tip with respect to the center of the wrist,
- \( u_{i} \) represents the vector between the center of wrist and the corresponding i-finger reference frame,
- \( 0T_{i}(\alpha_{i}) \) is a matrix that contains the homogeneous matrix between the i finger reference frame and its corresponding i-finger tip.

This matrix consists of the concatenation of matrices that represent the contribution of each i-finger joint displacement \( (\theta_{i,C}, \theta_{i,MCP,aa}, \theta_{i,MCP,fe}, \theta_{i,PIP}, \theta_{i,DIP}) \), rotation contribution of each joint is defined by the matrix \( j^{-1}T_{i}(\alpha_{i}) \). Where:

\[
j^{-1}T_{i}(\alpha_{i}) = \\
\begin{pmatrix}
\cos(\alpha_{i}) & -\cos(\alpha_{i})\sin(\alpha_{i}) & \sin(\alpha_{i})\sin(\alpha_{i}) & a_{i,j}\cos(\alpha_{i}) \\
\sin(\alpha_{i}) & \cos(\alpha_{i})\cos(\alpha_{i}) & -\sin(\alpha_{i})\cos(\alpha_{i}) & a_{i,j}\sin(\alpha_{i}) \\
0 & \sin(\alpha_{i}) & \cos(\alpha_{i}) & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\]
The direct kinematics of the thumb is presented in equation 3 in a similar way as for the fingers.

\[
P_T = s_0^{-1} T_{s_0} s_0 T_{s_0} s_0 T_{s_0} s_0 T_{s_0} s_0 T_{s_0} s_0 T_{s_0} s_0 T_{s_0} s_0 T_{s_0} (3)
\]

Where terms in this equation are:
- \( p_T \) represents a matrix that contains position and orientation of the thumb finger tip with respect to the center of the wrist,
- \( u_T \) represents the vector between the center of wrist and the corresponding thumb reference frame,
- \( T_{s_0} (\theta_i) \) is a matrix that contains the homogeneous matrix between the thumb reference frame and its finger tip.

This matrix is also a concatenation of the corresponding matrixes; which are obtained by the thumb joints(\( \theta_{T, MCP} \)). [13] [14]

4. Measurements of phalange dimensions

Data measured was collected from a set of 5 volunteers who participated in the research, referenced as S1, S2, S3, S4 and S5 in following data presented. Phalange dimensions were collected for all fingers including the thumb, seen in table 1. Additional measurements were done to determine the distance between the fingers between the MCP joints, shown in table 2. Two examples can be seen in figure 3. Blue segments correspond to the proximal phalange; green corresponds to the intermediate phalange while the purple segment corresponds to the distal phalange of the finger.

**Figure 3.** – Phalange dimension analysis.

**Table 1.** Phalange dimension measurements

|       | Thumb | Index | Middle | Ring | Little |
|-------|-------|-------|--------|------|--------|
|       | Proximal | Distal | Proximal | Distal | Proximal | Distal | Proximal | Distal | Proximal | Distal | Proximal | Distal |
| S1    | 34.1  | 27.7  | 35.1  | 26.1  | 23.6  | 39.7  | 31.3  | 23.3  | 38.6  | 27.8  | 25.0  | 32.3  | 22.8  | 20.8  |
| S2    | 38.1  | 30.9  | 46.1  | 26.4  | 21.1  | 50.6  | 31.7  | 24.0  | 37.7  | 33.3  | 24.7  | 28.5  | 18.7  | 21.6  |
| S3    | 34.5  | 25.9  | 30.2  | 23.6  | 21.7  | 36.0  | 24.6  | 24.7  | 28.0  | 27.2  | 22.4  | 23.0  | 18.1  | 19.4  |
| S4    | 32.7  | 24.8  | 30.0  | 21.3  | 21.1  | 37.9  | 24.7  | 22.1  | 28.2  | 23.3  | 22.8  | 22.0  | 16.8  | 18.4  |
| S5    | 33.5  | 28.6  | 44.0  | 26.1  | 23.1  | 52.3  | 28.3  | 25.8  | 43.5  | 30.1  | 25.5  | 32.0  | 22.3  | 22.6  |

**Table 2.** – Distance between the fingers measured at the MCP joint

|       | S1 | S2 | S3 | S4 | S5 |
|-------|----|----|----|----|----|
| Index – Middle MCP Dimensions [mm] | 22.2 | 22.6 | 22.2 | 21.9 | 19.3 |
| Middle – Ring MCP Dimensions [mm] | 25.1 | 18.7 | 20.1 | 22.0 | 20.6 |
| Ring – Little MCP Dimensions [mm] | 23.0 | 20.2 | 19.8 | 21.8 | 18.9 |
5. Angular study of the phalange joints

Angles were measured on the phalange joints in the flexed position and in the extended position of the hand. The analysis can be seen in figure 4, where the flexion phase is shown on the left side and the extension phase is shown on the right side. During the flexion/extension exercises the subjects were asked to perform normal routine movements they would do in a normal day to day environment. It was noted that some subjects have a reflex to grasp the thumb while flexing the hand while others do not have this reflex. Another observation is that some subjects exhibit a tendency to extend past the 180° degree as seen in figure 3 – S1 and 3 – S2.

Table 3. Joint angle analysis results

|                | Flexion |               | Extension |               |
|----------------|---------|---------------|-----------|---------------|
|                | MCP Angle | PIP Angle | DIP Angle | MCP Angle | PIP Angle | DIP Angle |
| Subject 1     | 100      | 100          | 156       | 179         | 176       | 180       |
| Subject 2     | 129      | 107          | 133       | 194         | 178       | 179       |
| Subject 3     | 119      | 84           | 114       | 180         | 190       | 183       |
| Subject 4     | 119      | 79           | 99        | 176         | 183       | 177       |
| Subject 5     | 113      | 68           | 118       | 180         | 175       | 179       |

6. Joint trajectory

In this section of the paper trajectory of the joints are described using a series of motion graphs created from the data generated by tracking the movement of the key points mentioned in figure 1. Data created by Kinovea such as X, Y and time parameters were saved in excel format for 4 key measurement point corresponding with the MCP, PIP, DIP joints and an addition reference point at the end of the distal phalange. An important factor to mention is that an ideal hand does not exist as a baseline. Subtle or major differences between the subject’s hands will always generate unique trajectory patterns. As a result comparisons will be done between the individual subjects. This part of the study was done with 3 of the volunteers and was repeated 3 times for each volunteer. Graphs for flexion and extensions were made separately for better observation. In figure 5 the flexion movement of the fingers is represented in an X Y graph for the 3 tries of the exercise.
Important to note that during flexion the MCP joint also moves, influencing the trajectory of the PIP and DIP trajectory relative to a fixed frame of reference. This MCP movement during flexion and extension can be due to the rotation of the carpal joint or even the upper arm. As it is observed in the following examples, subjects have an involuntary tendency to also rotate the carpal joint while performing the exercises.

In figure 6 the extension movement trajectory of subject 1 can be observed. As to be expected in any biomechanical system each movement has a unique curve and trajectory, repeated exercises produce similar result but do not have identical characteristics.

The movement trajectory of subject 2 for the flexion exercise can be seen in figure 7. We can observe that the MCP joint moves significantly more in subject 2 compared to subject 1. This MCP join greatly influences the trajectory of the other joints.

![Figure 6. Subject 1 extension movement trajectory of key points.](image)

![Figure 7. Subject 2 flexion movement trajectories of key points.](image)

![Figure 8. Subject 2 extension movement trajectories of key points.](image)
In figure 8- b and c we can clearly see a slight curvature of the MCP joint trajectory due to carpal rotation during the extension phase.

The involuntary rotation of the carpal joint is part of the grasping movement of some subjects. In subject one there was little to none movement of the MCP joint due to carpal rotation, in subject two there was a noticeable effect in the joint trajectories while in subject 3 the carpal rotation is even more greater and with a bigger impact over the trajectory as seen in figures 9 and 10.

7. Conclusions
Taking into consideration the results from this paper, there are a number of aspects that were observed that should be taken into consideration for future research. One important factor in gathering anthropometric measurements using video processing is the accuracy of the video quality. Factors such as frame rate, resolution, good focus and good light conditions are essential when capturing video for processing. A study with more subjects on a larger scale can give more data valuable once a standard way of working is established regarding capturing and data processing. For future research it would be also interesting to observe the trajectory taking the MCP joint as a fixed frame of reference to the other joints. Velocity and acceleration would also be of value if analyzed in future work. In general the data collected and generated proved to be important in designing and developing rehabilitation devices that have a better compliance to the wearer.
8. References

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