AN ENCHANCED KINEMATIC MODEL OF THE HUMAN THUMB FOR AN ARTIFICIAL HAND

Marc Franke and Martin Bogdan
Department of Computer Engineering, Institute for Computer Science
University of Leipzig, Johannisgasse 26, Leipzig, Germany

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Abstract: Hand prostheses need to be lightweight, robust and forceful and should replace the function and range of performance of the human hand in the best possible way. Furthermore, their look and appearance should turn up as naturally as possible. The prostheses and anthropomorphic robot hands known today often lack one or more of those aspects. We assume that the kinematic function of the thumb is additionally supported by the kinematic function of the STT (Scaphoid-Trapezium-Trapezoid) joint, which builds the radial carpal column. Our study is based on a previous work by Essers (Essers, 2006) determining the specific movements of the STT joints. In this study, these results were combined with a kinematic 3D model of the human hand with focus on the kinematic of the radial carpal column. We set up a kinematic chain of the radial carpal column and the thumb bones to analyse the data gained from the measured movements. The simulations revealed, that the joint movement of the STT joint supports up to $1/3$ of the motion range of the adduction, abduction, flexion and extension. Based on these results, we integrated the previous findings into a real kinematic model of the human thumb.

1 INTRODUCTION

The opposability and circumduction of the thumb is in medical-anatomical literature usually contributed to the biomechanical function of the CMC (Carpometacarpal) joint between the trapezium and the 1st metacarpal. The CMC joint of the thumb enjoys great freedom of movement due to its saddle-shaped articular surfaces. It's movements are flexion and extension, abduction and adduction, pronation and supination. Hence, previous robot hands are commonly based on CMC joints providing a simplified kinematic with up to 2 DOF (flexion and extension, abduction and adduction). Anatomically more precise the CMC joint is synonymously named trapeziometacarpal joint because of the os trapezium which connects the 1st metacarpal with the carpus. In this approach, an enhanced kinematic model of the human thumb is presented, based on our analysis of a detailed morphologic-kinematic model of the carpus and the thumb. We state that the kinematic function of the thumb is supported by the kinematic function of the STT (Scaphoid-Trapezium-Trapezoid) joint, which builds the radial carpal column. Our study is based on a previous work by Essers (Essers, 2006) determining the specific movements of the STT (Scaphoid-Trapezium-Trapezoid) joint in a set of cadaver hands. In our study, we combined these results with a kinematic 3D model of the human hand, with focus on the kinematic chain of the radial carpal column. We set up a kinematic model of the radial carpal column and the thumb bones to analyse the data gained from measured motions. Based on these results, we set up a real kinematic model of the human thumb and integrated the previous findings. Our objective is the development of more sophisticated prosthetic hands to reconstruct the function of the natural hand in the best possible way.

2 ANALYSIS OF THE ARTICULATION OF THE THUMB AND THE RADIAL CARPAL COLUMN

The hand's function and grasping capabilities are fundamentally supported by the complex articulation of the thumb. The posture of the thumb has a main contribution to the elementary grasp

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types of the hand (McKenzie, 1994). In medical-anatomical literature the carpometacarpal articulation of the thumb is commonly explained by the function of the trapeziometacarpal joint between the first metacarpal (os metacarpale pollicis) and the trapezium. The trapeziometacarpal joint is synonymously and more commonly named carpometacarpal (CMC) joint. The CMC joint of the thumb enjoys great freedom of movement due to its saddle-shaped articular surfaces, as described in (Dornblueth et al., 1998), (Rauber and Kopsch, 2003), (Frisch, 2001), (Speckmann and Wittkowski, 1998), (Cooney et al., 1981). It's movements are flexion and extension, abduction and adduction, circumduction and opposition. Hence, artificial hands with more complex kinematics are commonly based on CMC joints with 2 degrees of freedom (DOF) (Butterfass et al., 2001), (Liu et al., 2007), (Lovchik and M.A.Diftler, 1999), (Wilkinson et al., 2003), (Wilkinson et al., 2003), (Schulz et al., 2005) which rotate around fixed joint axes.

(Essers, 2006) describes detailed experimental results of examining the STT (Scaphoid-Trapezoid-Trapezium) joint of the human hand using a set of cadaveric hands. In this experiment the motion of the scaphoid and trapezium during abduction, adduction, extension and flexion of the CMC joint has been measured and recorded by the use of a 3D tracking system. Fig. 2 shows a model of the radial carpal column and the skeleton of the thumb.

We configured a kinematic model of the carpal bones to simulate the joint movements. The kinematic transformation of the thumb including STT joint is:

$$
\begin{aligned}
{}^{R}T_{T_1} &= \left(\begin{array}{c|c} {}^{R}\mathbf{R}_{T_1} & {}^{R}\mathbf{x}_{T_1} \\ \mathbf{0} & 1 \end{array}\right) && (1)\\
&= {}^{R}A_{S_{AA}}\,{}^{S_{AA}}A_{S_{FE}}\,{}^{S_{FE}}A_{S_{SP}} && (2)\\
&\quad {}^{S_{SP}}A_{T_{AA}}\,{}^{S_{AA}}A_{T_{FE}}\,{}^{S_{FE}}A_{T_{SP}} && (3)\\
&\quad {}^{T_{SP}}A_{M_{AA}}\,{}^{M_{AA}}A_{M_{FE}}\,{}^{M_{FE}}A_{M_{SP}} && (4)\\
&\quad {}^{M_{SP}}A_{P_{FE}} && (5)\\
&\quad {}^{P_{FE}}A_{I_{FE}} && (6)\\
&\quad {}^{I_{FE}}A_{T_1}\;. && (7)
\end{aligned}
$$

where (2) describes the scaphoid's abduction-adduction, flexion-extension, and supination-pronation kinematic axes.
(3) describes the trapezium's abduction-adduction, flexion-extension, and supination-pronation kinematic axes.
(4) describes the metacarpal's abduction-adduction, flexion-extension and supination-pronation.
(5) describes the flexion-extension of proximal phalanx.
(6) describes the flexion-extension of distal phalanx.
(7) describes the constant translation from distal phalanx to TCP 1 (Tip Center Point).

3 SIMULATION AND ANALYSES OF THE WORKSPACE WITH FORWARD KINEMATICS

3.1 Experimental Short-description and Simulation Basics

The experimental setup from Essers (Essers, 2006) is displayed in Fig. 1. The thumb's TCP has manually been moved in a circumduction with a defined diameter of 100 *mm* by using the maniplation bar and the guidance ring. During this circumduction, the coordinates of the scaphoid and trapezium in the radial column have been measured and recorded by a 3D space track system.

In the kinematic chain, the movements of the scaphoid and trapezium measured by Essers describe a contribution to the movement of the TCP. The MCP and IP joints are in this case assumed as to be fixed and the motion of the CMC has not been recorded. The data in (Essers, 2006) has been taken on a set of 7 cadaveric hands, average and deviation were calculated and documented. Using the kinematic model we simulated the circumduction by forward kinematics, using the recorded coordinates (x, y, z, rx, ry, rz) for scaphoid and trapezium. The circumduction diameter and the distance between TCP and CMC have been taken from the experimental setup documentation. The simulation of the kinematic chain revealed the motion of the CMC joint. Hence, the contribution of STT motion and CMC to the circumduction movement of the TCP in workspace could be calculated.

3.2 Setup of the Kinematic 3D Model

The kinematic model has been configured by combining 3D data of an average sized adult hand skeleton with the forward kinematics given in (1). The manipulation guidance ring Fig. 2 (a) has been positioned aequivalent to the experimental setup in (Essers, 2006). It's diameter is required to determine the corresponding TCP circumduction diameter. By rotating the complete thumb around the radius given by the guidance ring, the TCP circumduction workspace is generated. The data for scaphoid and trapezium movements documented in (Essers, 2006) has been integrated into the 3D model to generate the partial

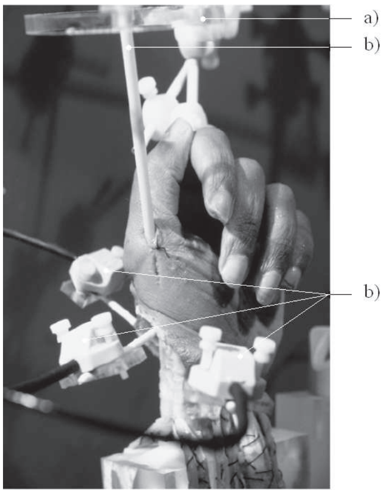

Figure 1: Experimental setup from (Essers, 2006) (printed with permisson) The experimental setup: Prepared cadaveric hand and sensors. a) Manipulation guidance ring. b) Manipulation bar. c) Space track sensors, attached to radius, saphoid and trapezium.

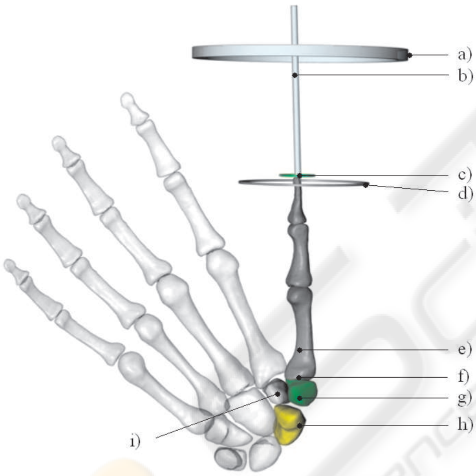

Figure 2: Setup of the kinematic 3D Model: a) Manipulation guidance ring. b) Manipulation bar. c) TCP (tip center point) of the thumb. d) TCP circumduction plane. e) Os metacarpale 1. f) CMC joint. g) Os trapezium. h) Os scaphoid. i) Os trapezoid.

trajectories of the scaphoid and trapezium during circumduction. The combined and seperated adoption of the data generated different combined and decomposed trajectories for trapezium and scaphoid articulation during circumduction of the thumb.

4 SIMULATION RESULTS

Workspace simulation and decomposition relvealed, that the STT joints articulation contribute 22% ± 11,47 of the TCP circumduction workspace of the thumb. Fig. 3 visualizes the results of the simulation. The combined partial workspace of scaphoid and trapezium (Fig. 3 (a)) can be decomposed into the scaphoid's and trapezium's component. The scaphoids partial TCP workspace (Fig. 3 (d) and (e)) turned out as more elliptical shaped.

5 ENHANCED ARTIFICIAL THUMB PROTOTYPE FOR A PROSTHETIC HAND

How can the previous results be used to improve the function of an artifial hand?

The STT and CMC joints are located in the metacarpus and they provide a very compact morphological structure. Therefore, a compact functional model of anatomic size can not easily be implemented. According to (McKenzie, 1994), the grasping function of the hand is mainly determined by 4 main areas in the thumb's workspace:

- Pad opposition
- Palm opposition
- Side opposition
- Virtual Finger

We combined this issue with our further results and implemented an artificial thumb based on an actuated STT joints with 1 active rotation DOF and 1 passive elastic rotation DOF. The active rotation DOF combines the ulnar and opposition-reposition axis (abduction-adduction and supination-pronation) measured in (Essers, 2006). As a result, the metacarpal articulation is supported and the thumb's workspace is enhanced. The passive elastic rotation DOF is underactuated and combined with the thumb's CMC, PIP and DIP flexion and extension. The corresponding kinematics is given by the transformation:

$$
\begin{aligned}
{}^{R^{\sim}}T_{T_1} &= \left(\begin{array}{c|c} {}^{R^{\sim}}\mathbf{R}_{T_1} & {}^{R^{\sim}}\mathbf{x}_{T_1} \\ \hline \mathbf{0} & 1 \end{array}\right) && (8)\\
&= {}^{R^{\sim}}A_{ST_{AASP}} \; {}^{ST^{AASP}}A_{ST_{FE}} && (9)\\
&\quad {}^{ST_{FE}}A_{M_{AA}} \; {}^{M_{AA}}A_{M_{FE}} \; {}^{M_{FE}}A_{M_{SP}} && (10)\\
&\quad {}^{M_{SP}}A_{P_{FE}} && (11)\\
&\quad {}^{P_{FE}}A_{I_{FE}} && (12)\\
&\quad {}^{I_{FE}}A_{T_1} \; . && (13)
\end{aligned}
$$

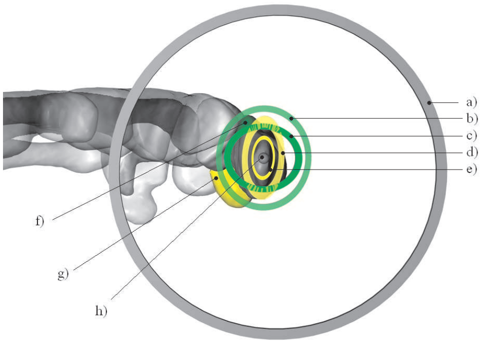

Figure 3: Simulation and decomposition of the Workspace of the thumb's metacarpal motion during circumduction: *a*) Workspace of TCP circumduction movement, combining CMC and STT articulation. *b*) Simulated TCP $(\mu+\sigma)$ workspace resulting from STT articulation with fixed CMC. (Partial scaphoid and trapezium movement.) *c*) TCP μ workspace of the same articulation.
d) TCP $(\mu+\sigma)$ workspace resulting from Scaphoid articulation with fixed Trapezium and fixed CMC. (Partial scaphoid movement.)
e) TCP μ workspace of the former articulation.
f) Os trapezium.
g) Os scaphoid.
h) TCP of the thumb in center position.

where (9) describes the simplified STT articuation with combined abduction-adduction and supination-pronation kinematic axes. ${}^{AASP}A_{ST_{FE}}$ describes the passive flexion-extension DOF.
(10) describes CMC (metacarpal base) articulation abduction-adduction, flexion-extension, and supination-pronation kinematic axes.
(11) describes the flexion-extension of proximal phalanx.
(12) describes the flexion-extension of distal phalanx.
(13) describes the constant translation from distal phalanx to TCP 1 (Tip Center Point).
The partial TCP workspace resulting from the active DOF is represented in Fig. 4. Experimental postures of the enhanced artificial thumb prototype based on the kinematic chain (13) are displayed in Fig. 5. Postures in 5 *a*) - *c*) are based on the simplified STT joint. The extension posture (Fig. 5 *d*)) is positioned by a combination of the simplified STT joint and the passive extension joint.

6 CONCLUSIONS

This investigation revealed, that the carpometacarpal articulation of the thumb must be differentiated into the contribution of the trapeziometacarpal joint and the contribution of the STT joints. The simulation

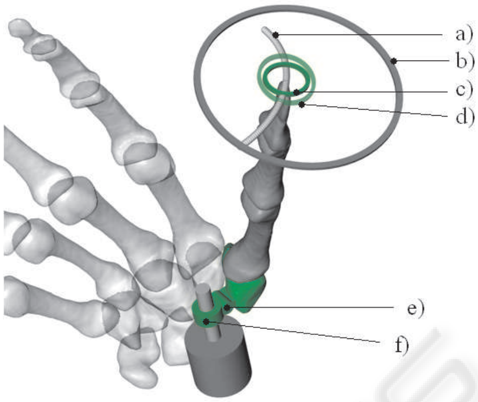

Figure 4: Enhanced artificial thumb model for a prosthetic hand. An active DOF in the region of the radial column articulates the main axis of the STT joints. It combines opposition-pronation and reposition-supination. It's corresponding TCP workspace crosses the TCP's neutral position and intersects the partial scaphoid-trapezium TCP workspace in Fig. 3 (*b*). *a*) TCP trajectory along simplified STT DOF.
b) TCP workspace combining CMC and STT.
c) Combined scaphoid and trapezium workspace (σ).
d) Combined scaphoid and trapezium workspace $(\sigma+\mu)$.
e) Passive flexion-extension DOF.
f) Active DOF combining opposition-pronation and reposition-supination.

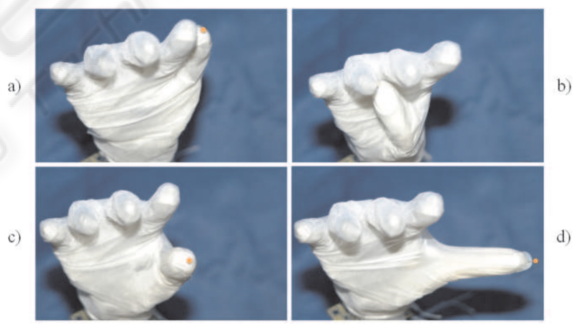

Figure 5: Experimental postures of the enhanced artificial thumb prototype: *a*) Retroposition, *b*) Opposition, *c*) Neutral position, *d*) Extension.

results revealed, that the joint movement of the STT joints supports up to $1/3$ (22% $\pm$ 11,47) of the motion range of the adduction, abduction, flexion and extension. The workspace of the thumb is significantly enhanced by the motion of the STT joints. Hence we propose, that adequate anthropomorphic models of the thumb should simulate the kinematics of the STT joints to approximate biomechanically correct movements. Currently simplified kinematic concepts of the articulation of the thumb - as presented in state-of-the-art robot and artificial hands - commonly disregard the fact, that the joint axes of the scaphoid and trapezium affect the trajectory of the thumb and it's TCP workspace.

The fact, that the rotation centre lies deeper in the radial carpal column corresponds to an extended workspace of the thumb. In the artificial thumb presented an STT joint with 1 active DOF and 1 passive, underactuated DOF is applied. As a result, the thumb's workspace is enlarged and biomechanically more adequate. Some examples for extreme postures of the thumb are given in Fig. 5 $a), b)$ and $d)$.

In combination with robust and forceful finger kinematics (Franke and Bogdan, 2009) biomechanically effective hand prostheses can be realised. We resume, that these properties are excellent qualifications for applications in the field of future hand prostheses, for example for biologically inspired neural prostheses (Bogdan and Franke, 2001) with an extended range of performance.

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REFERENCES

Bogdan, M. and Franke, M. (2001). Real time processing of nerve signals for controlling an artificial hand. In *Proceedings of the IASTED Conference on Applied Informatics 2001*. IASTED.

Butterfass, J., Grebenstein, M., and Hirzinger, H. L. G. (2001). DLR hand II: Next generation of a dexterous robot hand. In *Proceedings of the 2001 IEEE International Conference on Robotics & Automation*. IEEE Robotics & Automation Society.

Cooney, W., Lucca, M. J., Chao, E. Y., and Linscheid, R. L. (1981). The kinesiology of the thumb trapeziometacarpal joint. In *The Journal of Bone and Joint Surgery*. Journal of Bone and Joint Surgery, Inc.

Dornblueth, O., Zink, C., and Hildebrandt, H. (1998). *Pschyrembel - Klinisches Woerterbuch (in German)*. Walter de Gruyter, Berlin, 52nd edition.

Essers, F. (2006). *Untersuchung zur Kinematik im Bereich des Scapho-Trapezio-Trapezoidalgelenks der menschlichen Hand bei Zirkumduktion des Daumens (in German)*. F. Essers, Duesseldorf, 1st edition.

Franke, M. and Bogdan, M. (2009). A new lightweight, robust and forceful finger for an artificial limb. In *Proceedings of the 2009 World Congress on Medical Physics and Biomedical Engineering*. Springer.

Frisch, H. (2001). *Programmierte Untersuchung des Bewegungsapparates. Chirodiagnostik (in German)*. Springer, Berlin, 3rd edition.

Liu, H., Wu, K., Meusel, P., Hirzinger, G., Jin, M., Liu, Y., Fan, S., Lan, T., and Chen, Z. (2007). A dexterous humanoid five-fingered robotic hand. In *Proceedings of the 17th IEEE International Symposium on Robot and Human Interactive Communication*. IEEE Robotics & Automation Society.

Lovchik, C. and M.A.Diftler (1999). The robonaut hand: a dexterous robot hand for space. In *Proceedings of 1999 IEEE International Conference on Robotics and Automation*. IEEE Robotics & Automation Society.

McKenzie, C. (1994). *The Grasping Hand*. Elsevier Science, Amsterdam, 1st edition.

Rauber, A. and Kopsch, F. (2003). *Anatomie des Menschen, Band 1, Bewegungsapparat (in German)*. Toendury, Berlin, 3rd edition.

Schulz, S., Pylatiuk, C., Reischl, M., Martin, J., Mikut, R., and Bretthauer, G. (2005). A lightweight multifunctional prosthetic hand. In *Robotica*. IEEE Robotics & Automation Society.

Speckmann, E. J. and Wittkowski, W. (1998). *Bau und Funktionen des menschlichen Koerpers. Praxisorientierte Anatomie und Physiologie (in German)*. Urban & Schwarzenberg, Munic, 18th edition.

Wilkinson, D., Weghe, M. V., and Matsuoka, Y. (2003). An extensor mechanism for an anatomical robotic hand. In *Proceedings of the 2003 IEEE International Conference on Robotics and Automation*. IEEE Robotics & Automation Society.