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Method for Non-Invasive Skin Artifact-Free Spatial Bone Motion Tracking Using Pressure Sensor Foils

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This work addresses the development of a novel method for bone pose estimation that is both, non-invasive and accurate. The main principal is to palpate three prominent bone protuberances using pressure sensor planes attached to the skin. Bone protuberances are approximated by three ellipsoids that are rigidly attached together. The general formulation of the constraint equations is presented and, as a solution approach, an optimization cost function is proposed allowing bone pose tracking that is insensitive toward input errors. The method is validated in-vivo using dual fluoroscopy yielding bone tracking precisions in the submillimeter range and below 1 degree, thus, reaching the same order of magnitude as state of the art model based tracking techniques. Finally, the general approach is extended to automatically approximate the rigid body bone geometry via pressure sensor palpation that allows to fully circumvent radiation exposure, making this approach universally applicable.

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Preface

List of publications

The present thesis was developed as research associate at the Institute of Mechanics and Robotics ("Lehrstuhl für Mechanik und Robotik") at the University of Duisburg-Essen. Many of the contributions and concepts presented in this work were previously published in the following conference publication and proceedings:

- **N. Bufe**, and A. Kecskeméthy. Position analysis of a planar rigid-body tracked by three ellipse pressure points along straight lines. In *Proceedings of the 14th World Congress in Mechanism and Machine Science*, pages 474–482, Taipei, Taiwan, October 25–30 2015.
- **N. Bufe**, A. Heinemann, P. Köhler, and A. Kecskeméthy. An approach for bone pose estimation via three external ellipsoid pressure points. In *15th Int. Symposium on Advances in Robot Kinematics*, Grasse, France, June 27–30 2016.
- **N. Bufe**, G. Kuntze, J. L. Ronsky, and A. Kecskeméthy. Fluoroscopy Validation of Noninvasive 3D Bone-Pose tracking via External Pressure-Foils. In *Proceedings of the ARK 2018 16th International Symposium on Advances in Robot Kinematics*, pages 466–473, Bologna, Italy, July 1–5 2018.

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The completion of this thesis would not have been possible without our cooperation partners in Canada. First and foremost, I want to thank Prof. Janet Lenore Ronsky for opening the doors to her lab at the University of Calgary. Without her expertise and openness toward this project, the validation of the methods presented that have shaped this thesis would have been impossible. I would also like to thank her working group, in particular Gregor Kuntze, Payam Zandiyeh, Jessica Küpper and Alonso Figueroa for their valuable contributions and technical assistance. Special thanks go to Sarah Sanni and her family for their incredible hospitality making the stay comfortable and enjoyable.

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Finally, I could not be more fortunate to have a family that has always given me unconditional love and support. Without you, I would not be where I am today!

Duisburg, April 2019
Nikolas Bufe

Contents

Notation

In this thesis, general vectors are assumed to be decomposed in the target frame. For other decompositions, the notation ${}^{k}_{i}\underline{r}_{j}$ is used, where i denotes the frame with respect to which the motion is measured, j the target frame and k the frame of decomposition.

Furthermore, ${}^{i}\mathbf{R}_{j}$ denotes the rotation matrix transforming coordinates with respect to frame $\mathcal{K}_j$ into coordinates with respect to frame $\mathcal{K}_i$.

Abstract

The knowledge about skeletal kinematics is essential in many biomechanical and medical applications. However, an accurate, non-invasive and radiation-free method for bone motion tracking is still an open issue. This thesis addresses the development of a novel method for bone pose estimation that is both, non-invasive and accurate. The main principal is to palpate three prominent bone protuberances using pressure sensor planes attached to the skin. Bone protuberances are approximated by three ellipsoids that are rigidly attached together.

At first, the geometrical problem of the planar case is analyzed, where ellipsoids become ellipses and sensor planes become lines. After deriving the constraint equations describing the mathematical model of the system, Gröbner bases are used to find the number of possible solutions for two different numerically defined configurations of the lines and the ellipses. As a result, a maximum number of 32 different real solutions for the symmetrical and a maximum number of 64 different complex and real solutions for the general case are obtained. However, using the example of the symmetric case, it can be shown that the solution variety can be significantly reduced. From the 32 real solutions only three solutions are physically plausible, taking into account that pressure points are generated by an ellipse arc facing the lines.

This work also presents the general formulation of the constraint equations for the three dimensional case. As a solution approach, an optimization cost function is proposed including the squared minimal distances between sensors and ellipsoids allowing bone pose tracking that is insensitive toward input errors. Furthermore, a dual fluoroscopy validation of the method for three basic movements of the shank: flexion/extension, abduction/adduction and internal rotation is presented. It is shown that by pressure sensor palpation, bone tracking precisions of 0.5 mm to 1.0 mm and 0.3° to 0.6° can be attained with respect to dual fluoroscopy manual registration, thus, reaching the same order of magnitude as state of the art model based tracking techniques.

Finally, this thesis regards the limiting case where ellipsoids become points allowing the introduction of an automatable procedure approximating the rigid body bone geometry based on data from a previously performed bone pose measurement. Thereby, it is possible to fully circumvent radiation exposure that might be necessary to extract ellipsoid parameters from e. g. a computed tomography scan. Results indicate that deviations to the ellipsoid-approximated bone model are in the submillimeter range and may thus be negligible for many applications.