Qualification of Wrist Functional Performance During Dart Thrower's Movement

Author:
Nguyen, N; Pham, TH; Pathirana, PN; Babazadeh, S; Page, R; Seneviratne, A

Publication details:
Conference proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual Conference
v. 2018
Medium: Print
pp. 5790 - 5793
1557-170X (ISSN); 2694-0604 (ISSN)

Publication Date:
2018-07-01

Publisher DOI:
https://doi.org/10.1109/embc.2018.8513685

Qualification of Wrist Functional Performance during Dart Thrower's Movement

[1]Nhan Nguyen, [1]Trieu H. Pham and [1]Pubudu N. Pathirana, *Senior Member, IEEE*,
[2]Sina Babazadeh and [2]Richard Page,
[3]Aruna Seneviratne, *Senior Member, IEEE*

***Abstract*—Recently, numerous comprehensive studies have been concentrating on the intricate kinematics of the wrist joint functionality captured with dart thrower's movement. It is envisaged that the wrist capability in performing daily activities can be more accurately characterized or encapsulated in the dart thrower's movement. This study examines the characteristic function of wrist movements during dart-throwing motion using only gyroscopic data measured from inertial sensors. A multi-dimensional form of dart throwing trajectory is described using quaternion representation associated with distance metric to quantitatively validate the functional wrist performance between two cohorts; healthy controls and patients. Eight normal subjects and eight patients engaged in a series of clinical trials conducted after undergoing post-surgical reconstructive procedures of the wrist joint. The discriminative results in terms of silhouette clustering evaluation show that the use of distance metric values based quaternion trajectory is well-matched consistently with subjective expert assessments. Our proposed approach captures the relative motions underpinning the wrist joint instead of relying on the traditional measure based on the range of motion measure. Therefore, this paper proposes a reliable approach to dynamically capture the wrist functionality during dart thrower's movement; a movement envisaged to describe the ability to engage in daily life activities. These quantitative outcomes in terms of measurement consistency will provide insightful information in understanding the significant changes in wrist joint signatures associated with various scenarios.**

***Index Terms*—Dart Thrower's Motion, Inertial Sensor, 3D Motion Trajectory, Orientation Estimation, Distance Metric**

I. INTRODUCTION

Current techniques of quantifying the functionality of the wrist joint are essentially measuring the range of movement (ROM) in the anatomical planes including flexion-extension (FE) and radial-ulnar deviation (RUD) motions [1]. However, the wrist motions typically follow along an arc path from radial-extension to ulnar-flexion. The natural functional pattern of wrist movements in the oblique plane such as dart-throwing, hammering and fly-fishing, is encapsulated as *dart-thrower's motion* (DTM) [2]. It is unique to humans and contributed signficantly to the evolutionary advantages for *Homo sapiens* [3]. Due to the significance and intricateness of the wrist joint, many comprehensive articles have discussed the kinematics behind this exceptional movement. However, bio-kinematic characterization relating to the daily activities of DTM still requires further investigations [4].

Numerous kinematic studies of the wrist joint during the DTM have been conducted using a wide range of 3- dimensional analysis techniques such as marker-less bone registration [5], Computed Tomography (CT) [6], Magnetic Resonance Imaging (MRI) [7]. Nevertheless, these approaches are affected by the limited image acquisition speeds, high cost, occlusions and the radiation exposure [3]. Therefore, wearable devices such as Inertial Measurement Units (IMUs) have been considered to overcome such strains on the health care system and to facilitate monitoring the daily activities of patients [8]. Subsequently, beneficial advances in wearable inertial sensor technology allowed the measurement of wrist kinematics in examining the small differences based minor motion that can appraise a dart player's technical proficiency by monitoring the overarm throw movements [9], [10].

In this study, we propose a novel approach for characterizing the wrist joint movements employing only the angular rates measured from gyroscope readings of inertial sensors placed on two different positions which are on the palm and in the middle of the forearm. This indeed is expected to produce a mechanism to quantitatively and unobtrusively assess the functional performance of one of the most complicated joint of the human body.

II. SENSING SYSTEM AND EXPERIMENTAL SETUP

A. Inertial Sensors

The wrist kinematics were recorded using two BioKin units [11] associated with real time wireless communication capabilities. Inertial measurement sensors ("MPU-9150" from *InvenSense, Inc.*) contain a tri-axial accelerometer, a tri-axial gyroscope and a tri-axial magnetometer. The BioKin sensors have been benchmarked with the conventional multiple-cameras based motion tracking system (VICON T40S) [12]. In addition, in-built sensor fusion techniques and calibration routines were developed to deliver optimal sensing performance during the clinical experiments. The gyroscope full scale range is $\pm$ 2000°/sec. The output data of IMU sensors were sampled at 200 Hz. The data were analysed by using MATLAB software package (Mathworks, Natick, MA, USA).

*This work was supported by CSIRO's Data61.

[1]School of Engineering, Faculty of Science Engineering and Built Environment, Deakin University, Australia (ndn@deakin.edu.au, hph@deakin.edu.au, pubudu.pathirana@deakin.edu.au).

[2]Barwon Orthopaedic Research Unit, Barwon Health University Hospital Geelong, Geelong, Victoria, Australia (sbabazadeh@gmail.com, richard.page@deakin.edu.au).

[3]CSIRO's Data61, Australian Technology Park, Alexandria, New South Wales, Australia (aruna.seneviratne@data61.csiro.au).

B. Participants

Eight healthy subjects without any history of upper extremity injury and eight patients who had undergone wrist surgical procedures in the past were recruited in this research. Participants were aged ranges between 30 years and 70 years. The purpose of the study was explained to them and written consent was obtained from all participants prior to collecting data from the clinical experiment.

C. Clinical Trial

The experimental protocol was identical to the previously published study that examined wrist kinematic coupling and performance during functional tasks between control and patient subjects [11]. The clinical trials were organized and conducted at Barwon Orthopaedic Research Unit, University Hospital Geelong, Australia. The ethics for this research project has been approved by Human Research Ethics Committee of Barwon Health (Reference number: 14/88). Two IMU sensors were attached to the dorsal side in two different positions: on the middle of the forearm and on the dorsum of the hand as shown in Fig. 1. Both IMU sensors were synchronised simultaneously for data collection. This was refined with the data stream in the analysis stage. A short calibration trial was implemented through the recording with the wrist and forearm resting in neutral position (0° of FE and RUD) using a clinical goniometer.

Initially, the hands were placed on the table with both wrist and forearm were placing in a neutral position. This allowed subjects to keep the upper limb in a static posture and two IMU sensors were calibrated for decreasing the attachment errors of the sensors to the hand and forearm. From this starting point, subjects engaged in DTM to throw darts as close as possible to the bull's-eye of a dartboard. This functional task was required to be carried out three times repeatedly, and there was a stationary calibration period of 10 seconds between each throwing.

III. Methodology

A. Orientation Estimation

The time frames of DTM are relatively small, i.e. less than 200 ms [9], and the angular rates measured from the gyroscope are adequate to capture this specific motion with greater accuracy at a relatively short time frame. This avoids the need to use magnetometer and accelerometer measurements which are inherently subjected to significant errors due to magnetic field disturbances and linear accelerations.

A simple 10 second calibration of stationary movement was conducted in the initial resting state and applied in the pre-processing stage to mitigate the effect of gyroscopic drift, thus optimizing the accuracy of the proposed orientation estimation. Moreover, the original gyroscopic data were normalized and offset values were accounted by measuring the mode value of the gyro sensor data at a stationary state.

Palm rotational wrist kinematics were interpreted with respect to the distal forearm's coordinate frame due to the measurement in each respective coordinate frame. The DTM

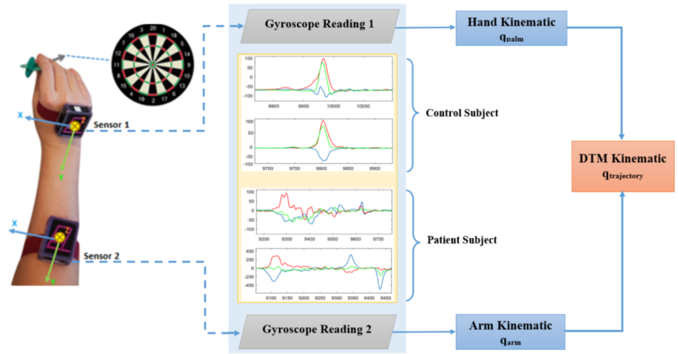

Fig. 1: Experimental setup (left) and data signal processing steps (right). Yellow area illustrates typical gyroscopic signals for control and patient subjects where the top figure is for the sensor placed on the palm and the bottom figure is for the sensor placed on the arm.

movements are captured in a dynamically changing orientation in the form of instantaneous rate of displacement of the wrist. This is represented by a quaternion metric; a four-dimensional vector with one real and three complex elements. Quaternion [13] is used in a wide range of application scenarios involving rotational dynamics and generally preferred over Euler angles or rotation matrix based approach to avoid the so-called singularity *Gimbal Lock* [14]. Based on the properties of quaternion representation of rotation, it is necessary to calculate the distance metric in the quaternion domain to measure similarity among various rotational quaternion trajectories when comparing the kinematic performance of DTM between two arbitrary subjects.

In order to measure the segment rotations, the time rate of change of the rotational quaternion is considered as a function of the angular velocity ω, typically measured by the gyroscope. At the first time *t = 0*, the arm and the palm are considered to be in a static state implying that their initial rotational quaternions are assumed as $q_0 = \begin{bmatrix}1 & 0 & 0 & 0\end{bmatrix}$. Let $q_w = \begin{bmatrix}0 & \omega_x & \omega_y & \omega_z\end{bmatrix}$ represents the original gyroscope readings around the respective local coordinate axis in quaternion notation. The temporal dynamics of the quaternion of gyroscopic data is shown in the following equation [15]:

$$q(t + \Delta t) = I_4 \times q(t) + \left[\frac{1}{2}.q(t) \times q_w\right] \Delta t. \qquad (1)$$

where:
$q_{(t+\triangle t)}$ is the quaternion at time $(t + \triangle t)$;
$\triangle t = 1/f_s$ is sampling interval;
f_s = 200 Hz (the default sampling frequency of IMU);
I_4 is the 4 x 4 identity matrix;
"$\times$" is quaternion multiplication;

The proposed orientation estimation approach assumes that the angular velocity is a constant value during sampling period $\triangle t$. From these equations, we can determine the orthogonal quaternions q_{palm} and q_{arm} at the palm and forearm positions from sensor 1 and sensor 2 as shown in Fig. 1 respectively. In particular, each sensor contains the relative information corresponding to the kinematic performance of the wrist joint and hence the use of two sensors are necessary to capture the relative wrist motions during DTM.

The quaternions at the palm location *(local coordinate frame)* with respect to the forearm location *(reference coordinate frame)* are obtained as follows:

$$ {}^{palm}_{arm}\mathrm{q} = {}^{palm}\mathrm{q} \times ({}^{arm}\mathrm{q})^{-1}. \quad (2)$$

Since each subject demonstrated three DTM repeatedly, it is necessary to determine an optimal DTM based rotational trajectory by visualizing the original gyroscope readings as shown in Fig. 1.

In order to find a set of quaternions representing a complete DTM trajectory, the transition quaternions are computed by the updating process using the previous quaternion at time $(t-1)$ to its new current quaternion at time t by following the equation [16]:

$$ q_{trajectory} = {}^{palm}_{arm}\mathrm{q}(t) \times ({}^{palm}_{arm}\mathrm{q}(t-1))^{-1}. \quad (3)$$

where q^{-1} is the inverse of quaternions.

The distance metric between the quaternion trajectories of two different subjects is measured as follows [31], [32]:

$$ D(q_R(i), q_T(j)) = |1 - q_R(i).q_T(j)| \,. \quad (4)$$

Here, $q_R(i)$ and $q_T(j)$ are the reference quaternion and the test quaternion between two elements i and j respectively.

B. Silhouette Clustering Analysis

In order to interpret and validate the consistency within clusters of examined datasets, Silhouette clustering technique is applied to provide a graphically concise representation of how accurate each subject belongs to its cluster [17]. Indeed, the Silhouette clustering evaluation is applicable consistently with any distance metric. The Silhouette value for each point is a measure of how similar that point is to points in its own cluster (*cohesion*), when compared to points in other clusters (*discrimination*). The Silhouette value for the *i*th point, S_i, is computed as follows:

$$ S_i = \frac{(b_i - a_i)}{max\,\{a_i, b_i\}}. \quad (5)$$

Here, a_i is the average distance from the ith point to the other points in the similar cluster as i, and b_i is the minimum average distance from the ith point to points in a different cluster, minimized over clusters. One can also increase the likelihood of the silhouette being maximized at the precise number of clusters by re-scaling the data using feature weights that are appropriately clustered .

IV. Results and Discussion

DTM is considered to be a fundamental pattern in numerous daily life activities. The ultimate goal is to determine the characteristic differences in circumduction arcs between normal and injured wrists due to the lack of wrist studies in post-surgical rehabilitation associated with many unknowns regarding the kinematics of DTM.

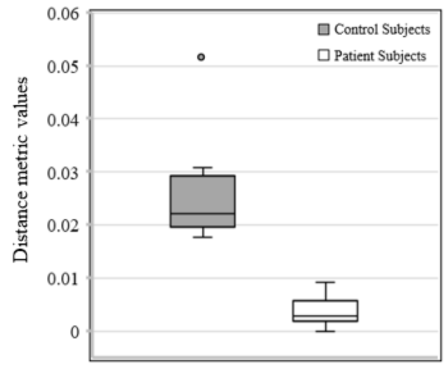

Fig. 2: Box-plots with the statistical distribution of the distance metric values of control and patient groups. On each box, the edges of the box are the 25^{th} and 75^{th} percentiles, the whiskers are the mean ± std, and data point beyonds the whisker is displayed as an outlier value using *dot* symbol.

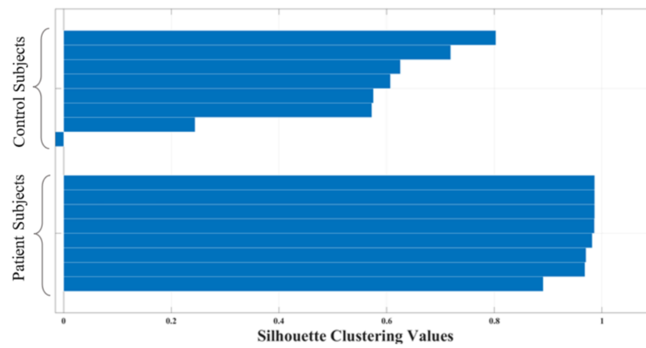

Fig. 3: Silhouette clustering evaluation of two clusters as controls and patients.

A. Statistical Analysis and Clustering Evaluation

The box-plots shown in Fig. 2 represent the significant difference between the median values of control and patient cohorts, which are 0.023 and 0.004 respectively. A considerable separation between the two cohorts is graphically detectable. Indeed, this figure elucidates the significant differences whereas non-overlapping confidence intervals indicate a significant difference at the chosen *p*-value with a tolerance of 5%. Furthermore, the two-sample *t*-test was performed to analyse statistical differences in the values of distance measure based quaternion trajectories between patient and control subjects. As a result, with a *p*-value of significantly 0.05 resulting from the distance metric values of all subjects, it is evident that, with 95% confidence, the true median values of patients and controls are considerably different. These outcomes have a strong agreement with previous study [8] that the functional performance via DTM were all significantly reduced in patients compared with healthy subjects indicating a relatively abnormal DTM. This result suggests that injured wrists may have a prejudicial effect on functional kinematic performance after surgical procedures.

In Fig. 3, there is an S value of the control group close to zero representing that the data is on the border of two groups. This also agrees with an outlier from the control cohort as represented in Fig. 2. Most points of controls are

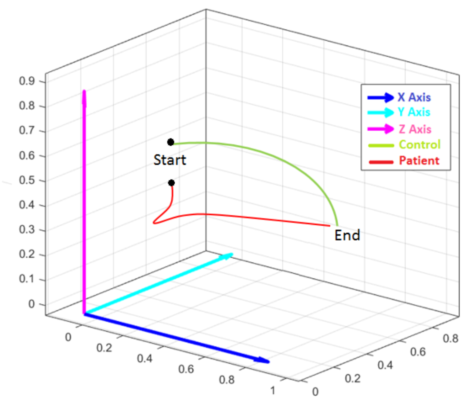

Fig. 4: Typical DTM rotational trajectories in 3D space of a control and a patient subjects.

higher than 0.624, indicating that the controls are relatively well-matched. The average S values for all patients is 0.969 which indicates that all patients are clustered appropriately within its own cluster.

B. Trajectory visualization

For a random control subject, Fig. 4 illustrates a typical tracjectory consistently similar to the normal DTM trajectories described in the literature [3] which were obtained using more sophisticated technologies utlizing multiple-cameras and optical marker clusters. On the other hand, it is evident to recognize that the DTM trajectory of the patient participant is of relatively arbitrary pattern. Therefore, the DTM trajectories of control and patient subjects are substantially different by visualizing the 3D rotational trajectories obtained from gyroscope measurement only.

V. Conclusion

In this work, we aimed at capturing the different characteristics in terms of kinematic performance in the wrist joint using dart thrower's movement which manifest evidently to be a more effective indication of the ability to perform daily life activities as well as the significant amount of reconstructive rehabilitation. Our findings suggest considerable differences regarding kinematics and functional performance between two different cohorts with the control group performing better on kinematic and performance variables in terms of distance metric values. These quantitative findings in terms of measurement consistency will form the foundation for understanding the significance of changes in wrist joint signatures associated with injuries, as well as changes in such signatures during rehabilitation. This becomes clinically important when designing specific post-operative rehabilitation protocols. Though these results are promising, there are still existing several limitations in our current study. Firstly, by using a historical cohort of normative data and patients after surgical operations as references, we were unable to compare the outcomes to preoperative function. Lastly, the small sample size of the trial subjects could under-represente the range of functional performance, limiting the ability of the results to be generalized. In future work, we will engage filtering model to fuse the inertial sensor's measurements and conduct trials with larger numbers of participants.

Acknowledgment

This work was supported by Australian Federal and Victoria State Governments and the Australian Research Council through the ICT Centre of Excellence Program, National ICT Australia (NICTA) and CSIRO's Data61.

The inertial sensors which are trademarked as $BioKin^{TM}$ used in this research were developed by Networked Sensing and Control (NSC) laboratory at Deakin University.

References

[1] Z.-M. Li, L. Kuxhaus, J. A. Fisk, and T. H. Christophel, "Coupling between wrist flexion–extension and radial–ulnar deviation," *Clinical biomechanics*, vol. 20, no. 2, pp. 177–183, 2005.

[2] N. Capener, "The hand in surgery," *Bone & Joint Journal*, vol. 38, no. 1, pp. 128–151, 1956.

[3] S. W. Wolfe, J. J. Crisco, C. M. Orr, and M. W. Marzke, "The dart-throwing motion of the wrist: is it unique to humans?" *journal of Hand Surgery*, vol. 31, no. 9, pp. 1429–1437, 2006.

[4] H. Moritomo, E. P. Apergis, G. Herzberg, F. W. Werner, S. W. Wolfe, and M. Garcia-Elias, "2007 ifssh committee report of wrist biomechanics committee: biomechanics of the so-called dart-throwing motion of the wrist," *Journal of Hand Surgery*, vol. 32, no. 9, pp. 1447–1453, 2007.

[5] S. W. Wolfe, C. Neu, and J. J. Crisco, "In vivo scaphoid, lunate, and capitate kinematics in flexion and in extension," *Journal of Hand Surgery*, vol. 25, no. 5, pp. 860–869, 2000.

[6] T. Moojen, J. Snel, M. Ritt, J. Kauer, H. Venema, and K. Bos, "Three-dimensional carpal kinematics in vivo," *Clinical Biomechanics*, vol. 17, no. 7, pp. 506–514, 2002.

[7] H. Moritomo, T. Murase, A. Goto, K. Oka, K. Sugamoto, and H. Yoshikawa, "Capitate-based kinematics of the midcarpal joint during wrist radioulnar deviation: an in vivo three-dimensional motion analysis1," *Journal of Hand Surgery*, vol. 29, no. 4, pp. 668–675, 2004.

[8] A. L. Wolff, R. Garg, A. P. Kraszewski, H. J. Hillstrom, J. F. Hafer, S. I. Backus, M. L. Lenhoff, and S. W. Wolfe, "Surgical treatments for scapholunate advanced collapse wrist: kinematics and functional performance," *Journal of Hand Surgery*, vol. 40, no. 8, pp. 1547–1553, 2015.

[9] M. Walsh, M. Tyndyk, J. Barton, B. O'Flynn, and C. O'Mathuna, "Biomechanical performance measurement using wireless inertial sensors for professional and recreational darts players," *British journal of sports medicine*, vol. 45, no. 15, pp. A10–A10, 2011.

[10] M. Walsh, J. Barton, B. O'Flynn, C. O'Mathuna, and M. Tyndyk, "Capturing the overarm throw in darts employing wireless inertial measurement," in *Sensors, 2011 IEEE*, 2011, pp. 1441–1444.

[11] N. Nguyen, T. Pham, P. N. Pathirana, S. Babazadeh, and R. Page, "Real-time measurement of radiocarpal joint angle during dart-thrower's movement," in *Biomedical Engineering International Conference (BMEiCON), 2015 8th.* IEEE, 2015, pp. 1–5.

[12] S. W. Ekanayake, A. J. Morris, M. Forrester, and P. N. Pathirana, "Biokin: an ambulatory platform for gait kinematic and feature assessment," *Healthcare technology letters*, vol. 2, no. 1, pp. 40–45, 2015.

[13] W. Hamilton, "On quaternions; or on a new system of imaginaries in algebra (letter to john t. graves, dated october 17, 1843)," *Philos. Magazine*, vol. 25, pp. 489–495, 1843.

[14] R. Goldman, "Understanding quaternions," *Graphical models*, vol. 73, no. 2, pp. 21–49, 2011.

[15] S. O. Madgwick, A. J. Harrison, and R. Vaidyanathan, "Estimation of imu and marg orientation using a gradient descent algorithm," in *Rehabilitation Robotics (ICORR), 2011 IEEE International Conference on.* IEEE, 2011, pp. 1–7.

[16] M. S. Ahmed and D. V. Ćuk, "Strapdown attitude algorithms using quaternion transition matrix and random inputs," *Scientific-Technical Review*, vol. 55, no. 1, pp. 3–14, 2005.

[17] P. J. Rousseeuw, "Silhouettes: a graphical aid to the interpretation and validation of cluster analysis," *Journal of computational and applied mathematics*, vol. 20, pp. 53–65, 1987.