Towards a homebased wrist range-of-motion training for children with cerebral palsy

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Abstract: This paper reports early-stage development results of a home-based gamified wrist rehabilitation training system for children with cerebral palsy (CCP). We propose a system composed of a wrist-worn inertial measurement unit (IMU) and a tangible device with an embedded IMU. We introduce a quaternion-based algorithm for real-time estimation of the range of motion (RoM) covered by adduction/abduction and flexion/extension motions of the wrist. Results of an initial proof-of-concept study with approximate ground truth show that the RoM can be determined with sufficient accuracy. A gamification concept is proposed that aims at providing biofeedback as well as motivating stimuli to CCP.

I. Introduction

In the SHArKi project, a technical support system for children with unilateral cerebral palsy (CCP) is being developed. By enhancing the children's motivation for home training, we aim at improving motor functions of their affected arm and hand. Therapists underlined the particular importance of wrist movements, which led to the development of a technical system using wristbands with inertial measurement units (IMUs) complemented by a cylindrical tangible device that contains an IMU as well, see Figure 1. While existing concepts with tangibles for upper limb rehabilitation focus on stroke patients, developments for CCP concentrate on tabletop or touch display games (examples in [1, 2]). Joining these approaches, we aim at a child-friendly and easy-to-use system that provides feedback on the achieved wrist range-of-motion (RoM). In the present contribution, we introduce a RoM estimation algorithm and a gamification concept that enables a playful wrist RoM training for CCP.

II. Material and methods

The ISB recommendations [3] define the forearm coordinates system as illustrated in Figure 1.

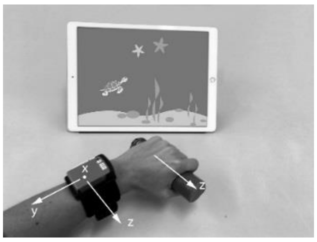

Figure 1: Proposed system (wristband and tangible device with IMUs) and local coordinate axes.

The wrist IMU is mounted to the wristband according to this coordinate system. Due to the cylindrical shape of the tangible device, its z-axis is approximately aligned with the mediolateral axis of the hand.

II.I algorithm to estimate wrist ROM

The algorithm can be divided into three main steps.

Step 0: orientation estimation
IMU-based orientation estimation [4] yields orientation quaternions for the forearm sensor (${}^F_E q$) and the tangible sensor (${}^T_E q$) in an inertial reference frame E. These quaternions are used to present the tangible axes in the forearm sensor coordinate system

$$ {}^T_F z = {}^E_F q \otimes^T_E z \otimes [0\ 0\ 0\ 1]' \otimes^E_T q \otimes^F_E q, \qquad (1)$$

where ${}^E_F q$ is the inverse quaternion of ${}^F_E q$. In the further description, all vectors are presented in the forearm coordinate axes $[{}_F x, {}_F y, {}_F z]$.

Step 1: calculate wrist angles
When the wrist moves, the coordinates of the tangible axes in the forearm coordinate system change. For the abduction/adduction (A/A) estimation, we project the tangible z-axes into the yz-forearm-plane by omitting its x-coordinate and determine the phase angle in that plane using the standard function atan2 with unwrap:

$$ \alpha = \mathrm{atan2}\,({}^T_F z[3], {}^T_F z[2]) \qquad (2)$$

For flexion/extension (F/E), we project the tangible x-axes into the xy-forearm plane and determine its phase angle:

$$ \epsilon = \mathrm{atan2}\,({}^T_F x[2], {}^T_F x[1]) \qquad (3)$$

Since the initial orientation of the tangible with respect to the hand is not known (depending on the grasp), the determined angles differ from the true wrist joint angles by an unknown offset. Nevertheless, if the subject moves back and forth between the minimum and maximum F/E or A/A angle, we can determine the corresponding RoM.

Step 2: define envelope and estimate ROM
A dynamic envelope is used to determine the minimum and maximum value that both angles reach during a performed

motion. To account for fatigue, the envelope shrinks automatically by 1°/s whenever the boundary values are not reached or exceeded. For A/A, the formalism is

$$a_{\mathrm{up}}(t) = \max\left(a_{\mathrm{up}}(t_{-1}) - 1°/s * T, \left(a_{\mathrm{up}}(t_{-1}) + \alpha(t)\right)/2\right) \quad (4)$$

$$a_{\mathrm{dw}}(t) = \min\left(a_{\mathrm{dw}}(t_{-1}) + 1°/s * T, \left(a_{\mathrm{dw}}(t_{-1}) + \alpha(t)\right)/2\right), \quad (5)$$

where t_{-1} denotes the previous sampling instant. For F/E the same formalism is used to determine ϵ_{up} and ϵ_{dw}. The RoM is determined as the difference between a_{up} and a_{dw} for A/A and ϵ_{up} and ϵ_{dw} for F/E, and scaled joint angles are determined as follows:

$$\tilde{\alpha}(t) = (\alpha(t) - a_{\mathrm{dw}}(t))/(a_{\mathrm{up}}(t) - a_{\mathrm{dw}}(t)) \quad (6)$$

$$\tilde{\epsilon}(t) = (\epsilon(t) - \varepsilon_{\mathrm{dw}}(t))/(\varepsilon_{\mathrm{up}}(t) - \varepsilon_{\mathrm{dw}}(t)) \quad (7)$$

II.II Gamification concept

A primary goal of the game is to motivate a child to perform repeated F/E motions at large amplitudes, which corresponds to $\tilde{\epsilon}$ exceeding 0.8 or falling below 0.2 regularly. To this end, the hand movements are visualized by a swimming turtle that moves up and down upon flexion and extension, respectively, and thereby avoids obstacles. At the top and bottom the turtle can collect stars as a motivating stimulus.

If the scaled angle exceeds 1.1 or falls below -0.1, a special reward is provided, e.g. the turtle jumps above the water surface. This offers an incentive for going beyond recent achievements, while the shrinking-envelope feature assures that the subject can continue playing even in the presence of fatigue. Speed levels and number of obstacles may be adapted to the child's capability, such that the game is perceived as a challenge without being overly demanding.

II.III Experimental procedure

Initial experimental trials were performed to provide a proof of concept for technical feasibility. Three healthy subjects used the proposed wristband and tangible device and wore an additional IMU on the back of the hand for approximate ground truth measurements. The sampling rate was 20 Hz. Subjects performed the following movements while seated at a table: (a) grasping, max. F/E (5 times), release, (b) grasping max. A/A (5 times), release, entire procedure repeated five times. One subject was asked to perform a longer trial with different RoM. Data analysis started when the tangible device was grasped. The RoM was estimated as described above, and ground truth values were determined from the relative orientation between the wrist IMU and the hand IMU.

III. Results and discussion

Figure 2 shows the result of the experimental procedure, a F/E movement curve. Starting with a small RoM, the wrist movement is increased and decreased after five repetitions.

The first two subplots demonstrate the envelope adaption (first subplot) and points of reward (crosses and stars in the second subplot) to the current game situation. In the third subplot the A/A and F/E RoM as determined by the proposed method and the approx. ground truth are shown. For the F/E movement the mean RoM difference between hand and tangible device is 6.6 ± 3 deg for F/E and 11,7 ± 5 deg for A/A. For the A/A movement the values amount to 10,1 ± 11,5 deg (A/A) and 4.9 ± 16.6 deg (F/E).

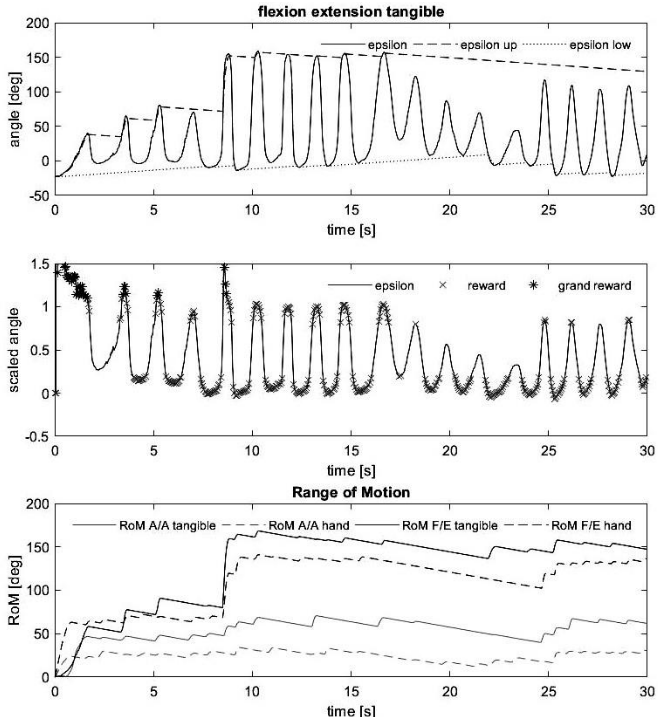

Figure 2: flexion and extension movement with a tangible device.

The probands reported that the maximal A/A movement was more difficult and unusual. A further examination shows that with increased ulnar abduction the index finger is relatively pushed forward, with radial abduction the finger shift is opposite. This might explain a larger RoM in the tangible sensor than in the hand sensor.

IV. Conclusions

Results show that the RoM can be determined with sufficient accuracy by inertial sensors at the wrist and inside a tangible device. As next steps, the proposed gamification concept will be implemented, and the system will be evaluated in trials with CCP.

AUTHOR'S STATEMENT

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