Measuring 3D Arm Movements for Activities of Daily Living

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ABSTRACT
Typical movements of the upper extremity in everyday life show a large variability between different, healthy subjects. In order to find reference arm movements for monitoring the progress of rehabilitation after stroke, we investigated the similarity of arm movement patterns on both sides of the body in healthy subjects for typical activities of daily living.

The movements of the upper extremity and the trunk, respectively, were recorded with a video-based 3D motion analysis system. Different statistical analyses of these data showed that the variability between the left and right body side of a subject is of the same size as the variability between different subjects. In other words, taking the movement trajectory of the healthy arm as a reference for the affected arm is not better than using the mean trajectory of a population as a reference, and simpler assessment criteria should be used.

Author Keywords
Arm movements, limb movement, activities of daily living, 3-dimensional, video, rehabilitation, quantitative assessment.

ACM Classification Keywords
J. Computer Applications, J.3 Life and Medical Sciences: Health

INTRODUCTION
While quantitative evaluations of leg movements are well established, for example in the analysis of gait [1], no such standards are available for arm movements. This lack of standards is caused mainly by two reasons: first, while the lower extremities are used predominantly for locomotion, hands and arms have to fulfill much more variable tasks. And second, the 3-dimensional analysis of arm movements is quite complex, and has only recently started to be addressed [2]{Rau, 2000 6396 /id}. This makes the rehabilitation of arm movements, for example after stroke, more difficult: What should we aim for when we want to achieve a "normal" arm movement? We hypothesized that while the variability of arm movements is large between different subjects, it might be significantly smaller within one subject, when the movement kinematics of the right and left arm are compared for the same, well defined task.

METHODS
Subjects
In total twenty students voluntarily participated in our investigations. A pilot study, which was used to optimize the arm movement tasks suitable for our investigation, comprised eight male and two female subjects (mean age 27.6 +/- 6.9 yr). Based on the subjects' own estimation, three of them were classified as "dominantly left handed", and seven as "dominantly right handed". In the main study seven male and three female subjects participated (mean age 26.0 +/- 3.8 yr). All subjects except one were dominantly right handed. All of them were healthy, with no upper extremity complaints.

Paradigms
For the upper extremity there is no single most relevant functional task determinable. Instead, researchers often specify a set of "activities of daily living" (ADLs) for their investigations. For our goal – finding repeatable reference arm movements – we chose arm movements similar to those during typical ADLs. To limit the degrees of freedom (DOFs), we chose to measure only the orientation of the upper arm relative to the thorax. Inclusion of lower arm and hand movements would add additional DOFs, further increasing the variability and complicating the analysis.

For each subject both upper extremities were measured for all three tasks specified below. These tasks were based on earlier studies [2] but were slightly modified to be more representative for ADLs. For all tasks, the subject was sitting in a chair without armrests. The subjects were instructed to keep their torso upright with no contact to the back of the chair. The thighs should be parallel and the knees roughly at an angle of 90 deg. To ensure repeatable starting conditions, each hand started palm down, on the ipsilateral knee. Each task was repeated five times. The subjects were instructed to execute the repetitions at a moderate speed that should be similar for the individual repetitions and body sides, respectively. The subjects also had to remain in the start and end position for approximately one second. The following three tasks were measured:

- *Reaching (Task 1)* Subjects started as described above. The end point was reached when the index finger touched a point marked on a metal bar in front of the subject. The point was located 10 cm above the top of the subject's head, in the plane that goes through the shoulder joint and parallel to the mid-sagittal plane, and at a distance where the subject could reach it by almost fully extending the elbow (Figure 1, left). This task represents activities such as taking something from a shelf.
- *Hand to contralateral shoulder (Task 2)* Again, subjects started as described above. The subjects were instructed to touch the contralateral shoulder with the tip of the index finger (Figure 1, center). This task represents all activities near the contralateral shoulder, e.g. zipping up a jacket or washing the arm-pit.
- *Hand to hip pocket (Task 3)* Again subjects started in the starting position as described above. The end position was reached when the hand was placed on the ipsilateral hip pocket (Figure 1, right). This task represents reaching the back and accomplishment of perineal care.

Recording System

Movements of the upper extremity and torso were recorded using the LUKOtronic AS202 system (Lukotronic, Innsbruck, Austria), a video-based motion analysis system, for tracking the positions of active LED-markers attached to the body segments. This system allows tracking of actively controlled infrared markers with sample rates up to 1200 Hz, within a measurement range of up to 5-7 m. The system has the advantage that it is easily portable. The motion capture unit is connected to a laptop via USB and requires no additional power supply.

For our study, all data were sampled at a frequency of 100 Hz. Since our study focused on the relative movement of the upper limb with respect to the trunk, we decided not

Figure 1. Arm movement tasks (left to right): Pointing to a target 10 cm above the head; pointing to the contralateral shoulder; moving the hand to the hip pocket.

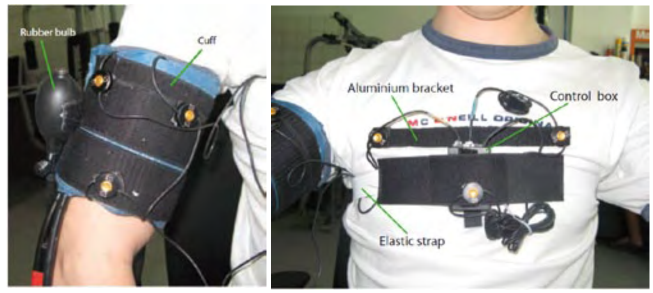

Figure 2. Markers attached to upper arm with a modified blood pressure cuff (left) and to the torso (right).

to monitor the complete anatomical chain (thorax - upper arm - lower arm - hand), but only thorax and upper arm. A total of six markers were attached to the subject - three on the upper arm und three on the trunk (Figure 2).

ANALYSIS

Description of Limb Movement

The data analysis was performed in Matlab (The Mathworks, Natick, Mass, USA), with programs developed in our group. Our investigation focused on the orientation of the arm relative to the torso. For each task, a representative trajectory was calculated by averaging the repetitions for each subject, body side and task.

We described the orientation of the upper arm relative to the trunk by using quaternions [3]. Compared to the more commonly used Euler angles, this method has two big advantages: it does not require a decomposition of the current orientation into a sequence of three consecutive rotations about arbitrarily chosen axes; and it avoids the problem of "gimbal lock" [4], which is unavoidable when using Euler angles.

To describe the orientation of the upper arm with respect to the torso, we define a torso-fixed coordinate system, with the x-axis pointing forward, the y-axis to the left, and the z-axis upward.

Evaluation of Limb Movement

Since the subjects performed the movement repetitions at different speeds, a normalization with respect to time is necessary before averaging. This is also essential for the subsequent comparison of different trajectories. An unavoidable consequence of time normalization is the loss of velocity information.

We perform the normalization with respect to time in two steps. First, the trajectory of each repetition is normalized to a length of 2000 data points. Depending on the duration of the repetition this can mean a shortening or a stretching of the data set. This normalization is accomplished by interpolation. Secondly, the duration of the phases in the trajectory is normalized. Therefore, each trajectory is divided into five phases that are defined by four characteristic points. These points have to be marked manually by the operator (for an example see Figure 3). Since we have five repetitions for each movement, this

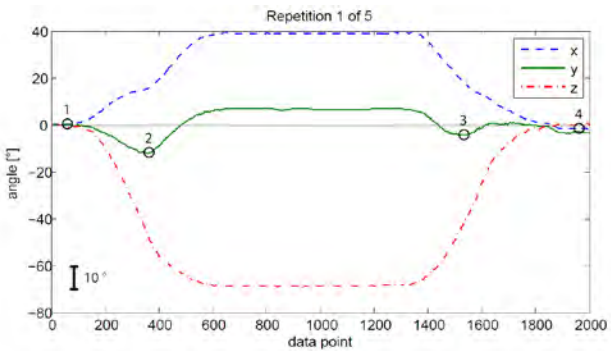

Figure 3. Single trajectory of the dominant arm, with the four characteristic points indicated by black circles.

marking results in five time coordinates for each point. Taking the median of these coordinates enables us to calculate the average duration for each phase. With these average durations the phases of all repetitions are normalized by interpolation. For a quantitative comparison of two trajectories a parameter has to be defined that describes the deviation between them. To obtain one single parameter, we decided to take the area between the two trajectories, as shown in Figure 4. This can be done either for each component separately; or it can be calculated by determining the difference between trajectories as a curving ribbon in 3-dimensional space.

Statistical Analysis

To minimize the variability in each subgroup, we distinguished between "dominant" and "non-dominant" arm. We analyzed three different pairings of data:

- Trajectory of subject's dominant arm compared to the trajectory of subject's non-dominant arm.
- Trajectory of subject's dominant arm compared to the mean trajectory of all dominant arms in the group.

Trajectory of subject's non-dominant arm compared to the mean trajectory of all non-dominant arms in the group.

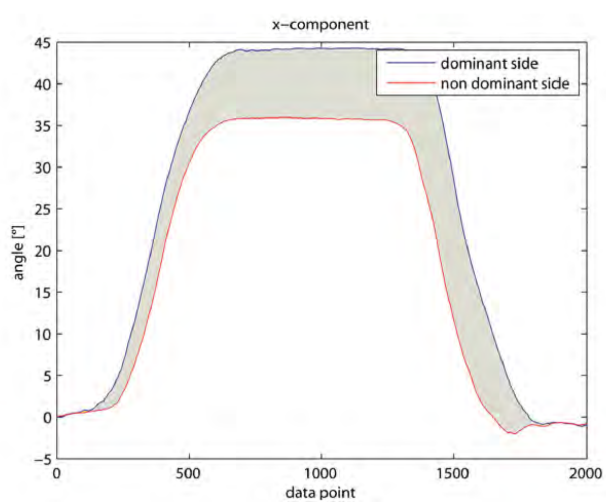

Figure 4. We characterized the deviation between two trajectories by the area between them (here marked in gray).

First we checked if our data come from normal distributions. This was done with the Lilliefors test, which is an adaption of the Kolmogorow-Smirnow test. The Matlab-command *lillietest* tests the null hypothesis that the data set comes from a normal distribution, against the alternative that it comes from a different distribution.

We tested the following two hypotheses:

- *Hypothesis 1:* The deviation between the trajectory of a subject's non-dominant arm and the average trajectory of all measured non-dominant arms is not greater than the deviation between the trajectory of a subject's dominant arm and the average trajectory of all measured dominant arms.
- *Hypothesis 2:* The deviation between the trajectory of a subject's dominant arm and the average trajectory of all measured dominant arms is not greater than the deviation between the trajectories of a subject's left and right arm.

In all our tests the significance level was set to $p<0.05$.

RESULTS

With one exception, all the pairings for all the tasks were normally distributed, which justifies our subsequent use of a t-test for the statistical data analysis.

To our surprise, none of the null hypotheses stated above could be rejected at a 5% significance level. Although the p-values for Task 3 are smaller than for the Tasks 1 and 2, the results do not give strong evidence that Task 3 is more appropriate for the evaluation of arm movements. Furthermore, there is no evidence that the separate analysis of the x, y and z component has any advantage over the three dimensional analysis.

DISCUSSION

We know that upper limb movements of the right and left side are to some extent coupled [5]. We also know that bilateral movement training can have significant beneficial effects in stroke rehabilitation [6;7]. What we don't know is how best to quantify arm movements, especially arm movements that have been recorded in three dimensions

Task	Hypo	dev 3d	dev x	dev y	dev z
1	1	87.1	67.4	92.0	73.2
1	2	66.2	87.9	23.6	56.6
2	1	70.1	83.6	72.0	31.4
2	2	79.0	35.9	87.5	67.7
3	1	51.2	52.9	77.5	25.0
3	2	52.0	31.9	52.3	54.6

Table 1. Results of the t-test for the main study, given in %. If the Hypothesis were wrong for a given Task, the corresponding value in the table would have to be less than 5%.

(3D). We also don't know how to optimize the training of unilateral arm movements during rehabilitation. The reason for these difficulties lies in the variability and complexity of arm movements, and in the lack of standards for recording and analyzing arm movements in 3D space [8].

We speculated that the variability of arm movements might be reduced by a) restricting the recording and analysis to relative movements between upper arm and thorax, during selected typical activities of daily living; b) eliminating temporal variability by normalizing the executed movements in time; and c) by referencing the arm movements to the movement of the contra-lateral side in healthy subjects, not to average movements of a normal population. This expectation was bolstered by the finding of Mackey et al, that in children with hemiplegic cerebral palsy, the range of motion (ROM), timing, and peak angular velocity of the unaffected arm were similar to the corresponding parameters of the dominant arm of healthy control children [9]. Similarly, Macedo and Magee found little difference in the ROM between the dominant and non-dominant arm in healthy subjects [10].

Somewhat to our surprise, the results of our investigations could not verify the hypotheses that we tested: it could not be shown that taking the movement pattern of the healthy arm as a reference for the affected arm is any better than using the mean trajectory of a population as a reference. Our study looked only for clear, reproducible correlations in the movement kinematics of right and left upper arm, which could provide a firm basis for new rehabilitation programs for arm movements. The detection of subtle correlations between right and left arm, or of gender related differences of movement kinematics, would require the inclusion of a larger number of subjects.

As handedness does not seem to be affected much by age [11;12], we speculate that the differences between our results and those from investigations looking only for difference in the ROM [9;10] are caused by the difference in the analysis: our analysis included the whole 3D trajectory of the movement, thereby highlighting any differences in any trajectory feature or component, while previous analyses focused on more global parameters such as ROM.

In summary, it can be stated that even for a well-defined set of movements that resemble activities of daily living, there is a large variability in the movement trajectories. Since both the individual variability between a person's left and right arm and the variability within the group are that large, meaningful reference parameters for a quantitative evaluation of arm movements have to be chosen carefully. Simple parameters like ROM are more likely to be successful than more detailed trajectory components.

REFERENCES

1. Perry, J. Gait Analysis: Normal and Pathological Function Slack Incorporated, 1992.
2. van Andel, C. J., Wolterbeek, N., Doorenbosch, C. A., Veeger, D. H., and Harlaar, J. Complete 3D kinematics of upper extremity functional tasks. *Gait Posture*, *27*, 1 (2008), 120-127.
3. Haslwanter, T. Mathematics of three-dimensional eye rotations. *Vision Res.*, *35*, 12 (1995), 1727-1739.
4. Hanson, A. J. *Visualizing Quaternions*, Elsevier, 2006.
5. Swinnen, S. P. Intermanual coordination: from behavioural principles to neural-network interactions. *Nat. Rev. Neurosci.*, *3*, 5, (2002), 348-359.
6. Stewart, K. C., Cauraugh, J. H., and Summers, J. J. Bilateral movement training and stroke rehabilitation: a systematic review and meta-analysis. *J. Neurol. Sci.*, *244*, 1-2, (2006), 89-95.
7. Goble, D. J. The potential for utilizing inter-limb coupling in the rehabilitation of upper limb motor disability due to unilateral brain injury. *Disabil. Rehabil.*, *28*, 18 (2006), 1103-1108.
8. Rau, G., sselhorst-Klug, C., and Schmidt, R. Movement biomechanics goes upwards: from the leg to the arm. *J. Biomech.*, *33*, 10 (2000), 1207-1216.
9. Mackey, A. H., Walt, S. E., and Stott, N. S. Deficits in upper-limb task performance in children with hemiplegic cerebral palsy as defined by 3-dimensional kinematics. *Arch. Phys. Med. Rehabil.*, *87*, 2 (2006), 207-215.
10. Macedo L. G., and Magee, D. J. Differences in range of motion between dominant and nondominant sides of upper and lower extremities. *J. Manipulative Physiol. Ther.*, *31*, 8 (2008), 577-582.
11. Rueckriegel, S. M., Blankenburg, F., Burghardt, R., Ehrlich, S., Henze, G., Mergl, R., and Hernaiz, D. P. Influence of age and movement complexity on kinematic hand movement parameters in childhood and adolescence. *Int. J. Dev. Neurosci.*, *26*, 7 (2008), 655-663.
12. Carlier, M., Dumont, A. M., Beau, J., and Michel, F. Hand performance of French children on a finger-tapping test in relation to handedness, sex, and age. *Percept. Mot. Skills*, *76*, 3, 1 (1993), 931-940.

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