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Short communication

Robot-based methodology for a kinematic and kinetic analysis of unconstrained, but reproducible upper extremity movement

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ABSTRACT

Although arm movements play an important role in everyday life, there is still a lack of procedures for the analysis of upper extremity movement. The main problems for standardizing the procedure are the variety of arm movements and the difficult assessment of external hand forces. The first problem requires the predefinition of motions, and the second one is the prerequisite for calculation of net joint forces and torques arising during motion. A new methodology for measuring external forces during prespecified, reproducible upper extremity movement has been introduced and validated. A robot-arm has been used to define the motion and 6 degrees of freedom (DoF) force sensor has been attached to it for acquiring the external loads acting on the arm. Additionally, force feedback has been used to help keeping external loads constant. Intra-individual reproducibility of joint angles was estimated by using correlation coefficients to compare a goal-directed movement with robot-guided task. Inter-individual reproducibility has been evaluated by using the mean standard deviation of joint angles for both types of movement. The results showed that both inter- and intra-individual reproducibility have significantly improved by using the robot. Also, the effectiveness of using force feedback for keeping a constant external load has been shown. This makes it possible to estimate net joint forces and torques which are important biomechanical information in motion analysis.

1. Introduction

Today, the standardised measurement of both three-dimensional kinematics and kinetics together with muscle activity using surface EMG (SEMG) is the usual procedure in clinical gait analysis (Chambers and Sutherland, 2002). Motion analysis systems in combination with underlying biomechanical rigid segment models (Kadaba et al., 1990; Davis et al., 1991) have been used to calculate joint angles. From these, other kinematic data such as joint velocity and acceleration of lower extremity movements can be determined. For the kinetic description of motion it is necessary to measure the forces acting on the body during movement. In gait analysis, those external forces are commonly acquired using force plates which detect the ground-reaction forces. The kinematic and kinetic data can then be used as inputs for a kinetic model (Bresler and Franke, 1950; Cavagna and Magaria, 1966), which calculates net joint moments and net joint forces.

However, there is a lack of methods for the assessment of arbitrary upper extremity movements, which are not restricted or repeatable, as compared to the movement's characteristic of gait (Rau et al., 2000). Many robot-assisted methods which can be end-effector-based (Hogan et al., 1995; Krebs et al., 1998; Burgar et al., 2000) or in form of an exoskeleton (Sanchez et al., 2006; Nef et al., 2007) have been used in rehabilitation for arm therapy. However, there are no reports on using robots in the motion analysis of upper extremities. The reason that disqualifies them from being used as a standard procedure in movement analysis is at least one of the following limitations: the investigated movement cannot be arbitrary, the movement is 2D, range of motion is limited, the method cannot be applied for activities of daily living, movement in one joint is disabled or the arm joint chain is not free.

Additionally, in contrast to gait, the external forces that are compensated by the neuromuscular system are less defined and have lower magnitudes. As a consequence, information about the forces and torques acting on the joints during upper extremity movements is often unavailable. Furthermore, the interpretation of the muscular-coordination pattern depicted by SEMG becomes complex and sometimes impossible. Human arm dynamics have been less investigated than the kinematics and the procedures

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were either task specific where the upper extremity kinetics has been analysed during crutch-assisted gait (Requejo et al., 2005) or during wheelchair propulsion (Ensminger et al., 1995); or without measured external loads (Riener and Straube, 1997).

For these reasons, there is a need for a methodology that not only improves the reproducibility of upper extremity movements but also defines and measures the external forces during any freely definable upper extremity movements.

2. Method

To enhance the reproducibility of upper extremity movement, 6 degrees of freedom (DoF) KUKA robot-arm (Fig. 1) was used to predefine the motion. For the measurement of the external forces on the robot's end-effector a 6 DoF force sensor with a ball-shaped handle had been attached. The subject held this handle during the movement test. Additionally, a force feedback about the current external load provided by a display connected to the sensor has been used to maintain a predefined force vector.

The display acts as a tool, which allows the definition of a target force in all degrees of freedom as well as a visualisation of the difference between the target and applied force vector. This target vector can be either constant or variable during a movement test. The insert in Fig. 1. shows two cases which may be displayed.

On the left-side, the applied force should be corrected since the target force vector is not achieved. The vector resulting from the difference between the two force vectors is presented on the screen as a black star. The position of the star on the screen depends on the manipulation of the handle by the subject and simultaneously indicates the direction in which the applied force vector should be corrected in order to move it into the target circle. On the right-side of the insert, the target force vector has been attained. As such the star has become green and is positioned in the central circle.

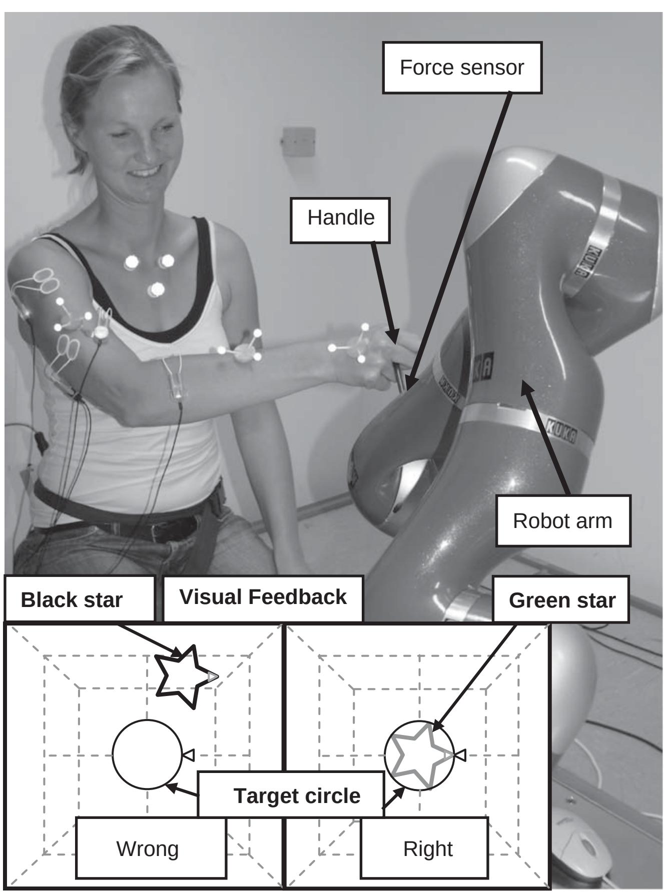

Fig. 1. Measurement system: a robot-arm presents a 3D path, 6 DoF force/torque sensor attached at the end effector and a handle used as a user interface between a subject and the force/torque sensor. Force feedback helps in maintaining a predefined force vector. Insert: on the left-side, the applied force should be corrected (target force vector is not achieved, the star is outside the target circle and black); on the right-side, target force vector is achieved (the star is in the target circle and green).

The experiments were performed on the dominant arm of eight subjects (5 male and 2 female) who participated in the study. They were all healthy, ages 22–32, and gave informed consent prior to the experiments.

3. Validation

3.1. Reproducibility of joint angles

For validation of the reproducibility of joint angles, a goal-directed movement was compared with the same motion guided by the robot. For this purpose, a relatively complex, three-dimensional daily activity referred to as 'Removing a parking token' (Williams et al., 2006) has been chosen. The subject was asked to perform three times the sequence of movements required to remove a parking token from a dispenser at the car-park, from a seated position in a car. The robot-guided movement was performed using the preprogrammed 3D motion path, also with three motion cycles. Both trials were repeated at least a day after the first measurement. For this movement, all three shoulder axes and flexion/extension axis in elbow joint are well defined, while the two hand axes and elbow pronation/supination axis are left free for subject to choose whether to use them or not. The joint angles were calculated (Schmidt et al., 1999; Williams et al., 2006) for the shoulder joint and flexion/extension axis in elbow joint for each trial.

The intra-individual reproducibility of the movement was evaluated using the Pearson product–moment correlation coefficients between the two independent trials for each rotational axis of shoulder and flexion/extension of elbow joint. Table 1 shows the mean values and standard deviations of the correlation coefficients obtained from the trials performed by 7 subjects.

The mean values of the correlation coefficients (Table 1) obtained for the robot-guided movement (0.66–0.87) were significantly higher ($p<0.001$) than those for the goal-directed movement (0.42–0.56). The ranges of the standard deviations of the mean correlation coefficient were 0.11–0.27 and 0.37–0.45, respectively.

In order to test the inter-individual variations in joint angles, the mean values and standard deviation of the second repetition in both trials have been calculated. The mean values of the standard deviations from 8 subjects for each measured joint axis were determined. Table 2 shows that they were significantly smaller ($p<$ 0.036) for the guided movement (7.28–21.78°) than for the goal-directed movement (9.59–27.5°).

3.2. Validation of the force feedback

For validation of the force feedback, 8 subjects performed three repetitions, with and without force feedback, of a shoulder flexion

Table 1
Mean values and standard deviations of the correlation coefficients of joint angles between two trials for the goal-directed and robot-guided task.

Movement		Goal directed	Robot guided
Correlation coefficients (mean value with standard deviation)			
Shoulder	Flex/ext	0.56 ± 0.39	0.81 ± 0.22
	Abd/add	0.55 ± 0.37	0.87 ± 0.11
	Inn/out	0.42 ± 0.45	0.66 ± 0.27
Elbow	Flex/ext	0.52 ± 0.39	0.79 ± 0.24

The flexion/extension (flex/ext), abduction/adduction (abd/add) and inner/outer rotation (inn/out) axes of the shoulder joint and the flexion/extension (flex/ext) axis of the elbow joint were considered.