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Using Kinect for upper-limb functional evaluation in home rehabilitation: a comparison with a 3D stereoscopic passive marker system *

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Abstract— **The functional evaluation of the upper-limb can be clinically assessed through the analysis of the kinematics, the dynamics, and measures of motor control. Such measures are usually obtained in a clinical environment with commercial stereoscopic 3D devices that allow to sample kinematics at high frequency and with high accuracy and precision, but that are, on the other hand, expensive, time consuming, and, most of all, are not portable. Consequently, such assessments are available only in clinics. With the aim of developing applications for neurological patients movement analysis in home environment, an experimental study has been conducted to compare the performances of a passive-marker motion capture system with the Kinect. Data were acquired simultaneously with the two systems during reaching against gravity movements. Results suggest that Kinect may be a valid tool for studying reaching against gravity and assessing upper-limb functionality at home in neurological patients.**

I. Introduction

Impaired motor control of the upper-limb is one of the most frequent consequences of stroke [1], [2]. The assessment of patients clinical course requires proper instruments to evaluate motor performances and their recovery. Passive-marker stereo vision systems for motion capture are commonly used in clinics for the assessment of human movements. Such systems allow to define anatomic points of interest and sample their position with high accuracy and high sampling rate. On the other hand, their use can be sometimes critical due to the time consuming procedures of marker positioning and errors related to them [3], [4], [5]. However, the importance to continue, monitor and evaluate the rehabilitation process outside the clinical environment has recently been addressed and discussed [6]. Because of their high price and non-portability, marker-based systems cannot be used outside the clinical environment. Therefore, methods that do not make use of markers could be of high interest because they are portable and affordable. Recently, low cost devices for human motion tracking have been developed, such as Microsoft Kinect and Asus Xtion [7]. Microsoft Kinect is a marker-less, cheap, portable and free programmable device that allows embedded motion tracking of 20 human joints (articular centers). The Kinect sensor was used to track human movement in rehabilitation and medical field to assess physiological movements [3], to monitor psychomotor exercises [8], to track orientation of the hand for tele-operation [9], to assist children with cerebral palsy [10], or young adults with motor disorders [11], to assist postures [12]. The aim of this study is to evaluate the applicability of the Kinect sensor for a functional evaluation of the upper-limb based on kinematic, dynamic and motor control measures and evaluations, through the analysis of reaching against gravity movement. Consequently, we provide a comparison between the BTS Elite and the Microsoft Kinect sensor as a candidate to substitute marker-based devices for upper-limb biomechanical evaluation, with the aim to be employed in a domestic environment.

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II. MATERIALS AND METHODS

A. Experimental Protocol

The experimental part of this study took place at ITIA - CNR Robotic Lab installed at Villa Beretta Rehabilitation Center (Costa Masnaga, LC). Four healthy subjects and one neurological patient were enrolled in the experiment. Their details are listed in Tab I. A fundamental motor task, representative of the upper-limb movement capabilities, was considered: reaching against gravity (RCH). Such movement was chosen since it is part of a rehabilitation protocol currently in use in clinics, that also includes hand-to-mouth movements (not considered in this study). [13], [14], [15]. During the execution of the RCH movements, a 6 TVC 3D-motion tracking system (SMART BTS, Italy) and a Microsoft Kinect Sensor for Windows (version 1.8, with SDK 1.8 release) recorded simultaneously the positions of shoulder, elbow, and wrist. Subjects were requested to perform 12 consecutive RCH movements (see Fig.3); the first and the last ones were not used for the analysis. Subjects sat on a stool with no backrest, 0.50 m from the ground. They were asked to keep the back straight and try not to move the shoulder. During RCH tasks, a marker was put as target reference at shoulder height, at a distance slightly longer

TABLE I: Subjects Data

Subject ID	Status	Sex	Age	Height	Weight
1	Healthy	F	25	165	54
2	Healthy	M	25	182	78
3	Healthy	M	28	179	64
4	Healthy	M	39	175	70
5	Stroke	M	70	171	75

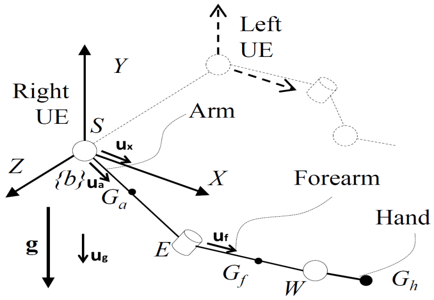

Fig. 1: Upper-Limb simple model.

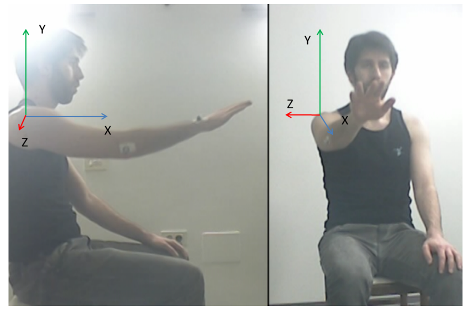

Fig. 2: Frame of reference.

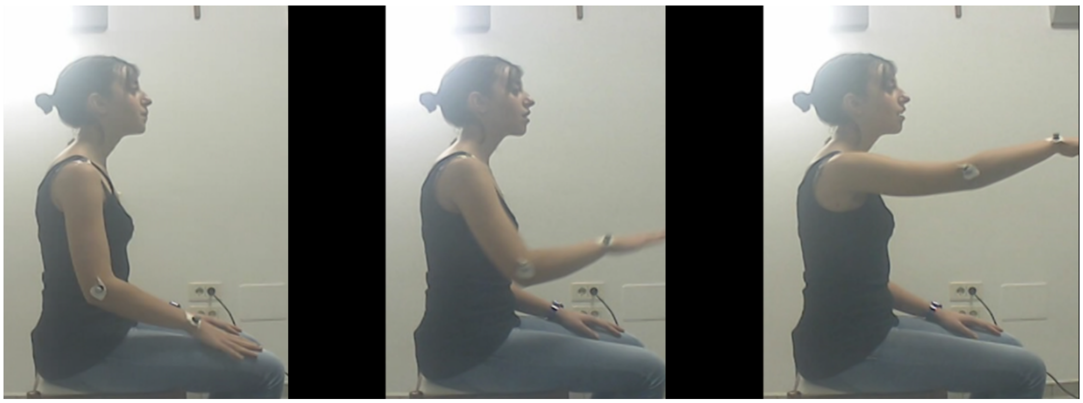

Fig. 3: The reaching movement

then the length of the whole upper-limb. The movement started with the hand on the thigh, and the task consisted in reaching the target by elevating the arm at about 90° degree and fully extending the elbow. [16]. Subject wore a sleeveless shirt for a correct marker application and to facilitate Kinect tracking, in order to minimize the errors. No procedure of pre-calibration of the sensor was tested, with the aim of keeping the acquisition procedures as simpler as possible. In fact, not only neurological patients could not be able of performing even simple calibration gestures, but also in a domestic environment the calibration procedure would be unsupervised and, consequently, less reliable.

B. Frame of reference

The frame of reference was chosen as follows: the x-axis points frontally in the sagittal plane, the y-axis points upwards in the vertical plane, the z-axis points rightwards in the transverse plane, as shown in Fig. 2.

C. Kinect

The Kinect sensor was aligned to the z-axis, placed frontally to the subjects, at a 2.0 meters distance from the body, at a 1.0 meters height from the ground, as suggested in Microsoft installation guidelines for a corrected motion tracking.

D. Marker placement

5 hemispherical retro-reflective markers were applied on the spinous process of D5, the spinous process of C7, the acromion, the lateral epicondyle of the elbow, and the styloid process of the ulna [13]. The first two markers served as reference while the others were representative of the shoulder, elbow and joint articulations respectively. A sixth marker was positioned a little higher than the shoulder, a few centimeters far from the fully extended configuration of the arm, and used as a target for the movement [16].

E. Joint centers estimation

The 5-markers protocol is currently in use in clinics to allow relatively fast acquisition and motion evaluation. In such protocol, markers are considered as representative of the joint centers. For the purpose of this study such approximation, negligible for some clinical approaches, was considered not negligible for a reliable data comparison. Some procedures to reduce the approximation errors were analyzed [17], [18], [19]. On the basis of [17], the shoulder joint center was placed 0.17 times the arm length translated vertically along the -y direction from the acromion. Under the hypothesis that the arm internal rotation is limited, and that the forearm does not pronate or supinate during reaching movements, the elbow position was translated towards the -z direction of 0.13 times the forearm length. A 0.10 times the forearm length fixed offset in the same direction was applied to the wrist.

F. Correction Effects

A comparison between shoulder, elbow and wrist marker positions, with and without the correction algorithm is shown in Fig. 4. Joint center positions will hereafter refer to

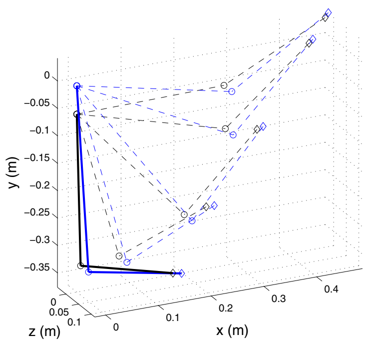

Fig. 4: Comparison between raw BTS data (blue) and after the articular center estimation procedure (black)

the corrected ones. The joint center estimation algorithm improves data reliability especially in locating the shoulder articular center.

G. Data processing

Recorded data were low-pass filtered (Butterworth filter, 3rd order, cutoff frequency 6Hz). As the Kinect sampling frequency was not constant, data were resampled at a fixed sampling rate (chosen as the average of the acquisition). BTS data were downsampled at the same sampling rate. At the end, the series were synchronized by manually selecting, for each series, the beginning of the second repetition and the end of the penultimate. Such temporal instants were put into correspondence. A correlation algorithm was implemented to verify the proper synchronization (not reported).

H. Upper-limb model

A simple upper-limb model was considered to compute kinematics and dynamics (Fig. 1). In analysis of human kinematics, a human upper limb is generally modeled as a linked chain of rigid body segments. The shoulder was modeled as a spherical joint, and the elbow as a single rotational joint. The following assumptions were introduced:

- only reaching movements are described;
- hand mass and motion are not included in the model;
- prono-supination movement is neglected.

The hand was not considered since the complexity of its geometry; prono-supination is minimal during reaching tasks for healthy subjects and high functional level patients. The biomechanical model was built by taking into account Levas [20] anthropometric tables. The model is fed with shoulder, elbow and wrist positions and computes the quantities described in the next paragraph.

I. Dependent Measures

The comparison focused on clinically significant kinematics, dynamics and motor control parameters [13]. Notation refers to Fig 1.

1) Kinematics:

- Shoulder elevation angle (*SA*) at full extension, computed as:
$$SA = \arccos(\vec{u_g} \times \vec{u_a}) \tag{1}$$
where (u_g, u_a) are the gravity-oriented unit vector and the arm unit vector respectively.
- Elbow flexo/extension angle (*EA*) at full extension, computed as:
$$EA = \arccos(\vec{u_a} \times \vec{u_f}) \tag{2}$$
where (u_a, u_f) are the arm unit vector and the forearm unit vector respectively. For neurological patients, full extension angles are intended to be the angles they produce at maximum extension.

2) Dynamics:

- Shoulder elevation torque (along z-axis of the reference system) at full extension.
Let (m_a, l_a) and (m_f, l_f) be the mass and length of the upper arm and forearm, respectively. The shoulder torque $\mathbf{T}_s$ can be computed as:
$$\mathbf{T}_s = \frac{d}{dt}\left[\mathbf{L}_a^S + \mathbf{L}_f^S\right] - \left[m_a\left(G_a - S\right) + m_f\left(G_f - S\right) + m_h\left(G_h - S\right)\right] \times \mathbf{g}, \tag{3}$$
where L_a^S and L_f^S are the angular momentums of the upper arm and the forearm w.r.t. the shoulder. For details refer to [16].
- Effort Index [21], computed as:
$$EI = \int_{t_i}^{t_f} T(t)\,\mathrm{d}t \tag{4}$$
where T is the shoulder elevation torque at time t.

3) Motor Control:

- Coefficient of Periodicity (CP). The repeatability between individual repetitions of reaching was evaluated by means of singular value decomposition pattern analysis (SVDPA). The result of the processing is a number between 0 and 1, referred to as the coefficient of periodicity (CP), the periodicity of movement value. The value corresponding to strictly periodic movements, that is, those which are repeated identically over time, is 1; as the movement loses periodicity, the CP gradually decreases. In the present study such analysis refers to acceleration repeatability, being more sensitive than displacement to pattern changes. In other words, the SVDPA was applied to the target-approaching acceleration to obtain the acceleration coefficient of periodicity (ACP). It follows that ACP can be considered as a measure of the consistency of the acceleration profiles across movements of each trial. For further details see [22], [23].
- Normalized jerk (NJ) index. The instantaneous distance between the marker of the wrist and the target marker is defined WTdistance. The smoothness of movement

was evaluated by jerk analysis (i.e., the third derivative) of the WTdistance. It has been shown that the time-integrated squared jerk decreases with increased smoothness of movement; it is therefore often used as a measure of the quality of selective motor control. [24] Jerk has been postulated to be a motion planning criterium adopted by our central nervous system [25]. NJ is computed as:

$$NJ = \sqrt{\frac{1}{2} \times \frac{d^5}{l^2} \int_{t_i}^{t_f} J^2(t)\,\mathrm{d}t}$$

where d denotes the overall movement duration, l denotes the overall movement length, and J denotes the jerk function.

III. RESULTS

A. Kinematics

Shoulder elevation angle on a reaching movement is shown in Fig. 5. Tab. III lists mean and standard deviation of the maximum elevation angle for all subjects. Elbow flexo extension angle during a reaching movement is shown in Fig. 6. Tab. III lists mean and standard deviation of the maximum extension angle for all subjects.

B. Dynamics

Shoulder elevation torque on a reaching movement is shown in Fig. 7. Table III lists mean and standard deviation of the maximum elevation torque for all subjects.

Tab. III lists effort indexes computed on ten repetitions of the movement. RMS error is not reported since the result is the integral of the whole trial.

C. Motor Control

Tab. III lists Normalized Jerk Indexes for all subjects, computed on ten repetitions of the movement. Tab. III lists Coefficient of Periodicity Indexes for all subjects, computed on ten repetitions of the movement.

IV. DISCUSSION

A. Kinematics

1) Shoulder elevation angle: The difference between Kinect and BTS in the angle computation is 3.32°±2.80°, which is considered acceptable and does not impact on the patient's performance evaluation.

2) Elbow flexo-extension angle: Elbow flexo extension angles were measured with a difference of 5.60°±6.35° at the end of the movement, when the arm is proximal to full extension. The mean error is acceptable. At the beginning and during the first part of the movement (low elevation angle), Kinect shows tracking errors in shoulder and/or elbow location. To assess such error, arm and forearm length were considered and are shown in Tab. II; *al* stands for 'arm length' while *fl* stands for 'forearm length'. The standard deviation of the Kinect upper-arm and forearm length measures are considerably higher than the ones of the marker-based system, and both upper arm and forearm appear as generally shorter. At the beginning of the movement, the patient's arm length measured with the Kinect is considerably shorter. This is considered to be the most remarkable difference and source of error between the two systems, and will be further investigated with other neurological patients. However, it is worth to mention that, from a clinical point of view, the full extension angle is the most significant measure, and it is only minimally affected by this arm length estimation error.

B. Dynamics

1) Shoulder elevation torque: The difference in shoulder elevation torque estimation is 0.38±0.37 Nm. Such value provides an acceptable precision.

2) Shoulder effort index: The effort index was considered as a parameter to evaluate the performance of the movement [21], especially for neurological patients. Comparisons were very promising since with both the marker-based system and the Kinect very similar values were computed, even if, as a consequence of the difference in the estimation of the torque, due to the sub-estimation of the patient's arm length, the Kinect slightly underestimated the effort index in the patient trial. Also the inertial component of the torque was slightly underestimated with Kinect data. Despite the high functional level of the patient, the difference with healthy subjects is apparent, suggesting the capability of coherent effort evaluations with Kinect.

C. Motor Control

1) Normalized Jerk: Two comparisons are shown in this section. Since the difference was found to be relevant, the Kinect NJ index was compared both to the NJ computed on BTS down-sampled frequency and to the BTS at its native frequency (see Tab. III). Downsampled BTS data fit the ones computed by Kinect, while BTS at its native (higher) frequency provides significantly higher values for NJ. As expected, the neurological patient, while being able to fully perform the motor task, has an higher NJ indicating worst motion control. Thus, while losing partial information due to lower sampling rate, the Kinect seems to correctly cluster healthy subjects and patients.

2) Coefficient of Periodicity: The CP is close to one for healthy subjects. This result indicates high capability of reproducing the same path and motion law while approaching the target. The Kinect seems to slightly overestimate the CP in respect to the BTS. It is worth to underline that, even for this index, the Kinect sensor seems to

TABLE II: Segments variability (m)

Sub. ID	BTS al	Kinect al	BTS fl	Kinect fl
1	0.305±0.013	0.234±0.029	0.240±0.003	0.201±0.012
2	0.358±0.015	0.284±0.026	0.266±0.001	0.212±0.013
3	0.334±0.011	0.269±0.031	0.244±0.040	0.191±0.010
4	0.346±0.008	0.252±0.028	0.256±0.002	0.212±0.011
5	0.352±0.010	0.232±0.030	0.257±0.004	0.211±0.018

detect the difference between a physiological movement and a pathological one, since the patient shows a lower CP index.

V. ACKWNOLEDGEMENTS

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VI. CONCLUSION AND FUTURE WORKS

The Kinect was tested using an upper-limb evaluation protocol during reaching tasks performed by healthy subjects and neurological patients. First results are promising since Kinect does not alter the upper-limb assessment protocol we proposed with the BTS system. Thus, Kinect can be considered as a valuable candidate, cheap and portable tool for biomechanical, kinematic, dynamic and motor control evaluation. Future works will be based on the enrollment of more healthy subjects and especially patients to have a wider statistical sample for the comparisons. When tracking patients' movement, the discrepancies between BTS and Kinect increase. Building a reference database will be useful to evaluate them properly. As a future development, we will use real time tracking to handle a software to give patients a feedback during rehabilitation sessions both at home and in clinics. More promising results are expected when the new Kinect sensor will be released.

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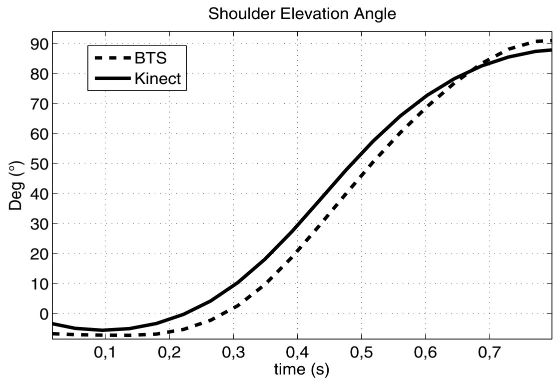

Fig. 5: BTS vs Kinect: shoulder elevation torque.

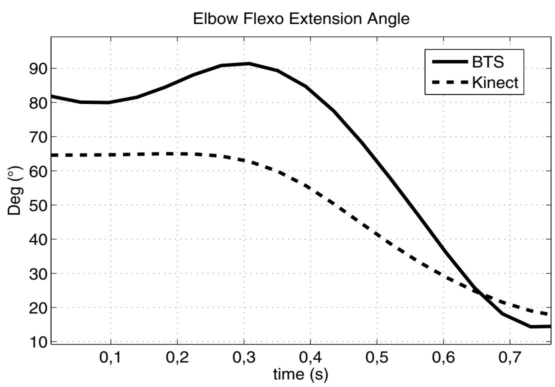

Fig. 6: BTS vs Kinect: elbow flexo-extension angle.

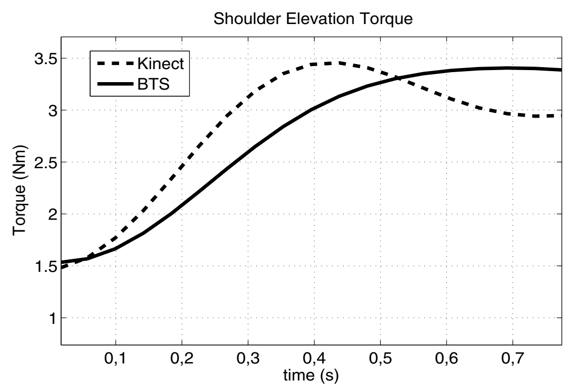

Fig. 7: BTS vs Kinect: shoulder elevation torque.

Subject	**SE (°)**		**EF (°)**		**T (Nm)**		**EI (Nms)**		**NJ**			**CP**		
	Kin	*BTS*	*Kin*	*BTS*	*Kin*	*BTS*	*Kin*	*BTS*	*Kin*	*BTS*	*BTShf*	*Kin*	*BTS*	*BTShf*
1 (Healthy)	88.4	90.1	18.2	15.1	3.2	3.5	38.9	38.3	10.1	12.6	12.5	0.96	0.94	0.94
	±1.3	±1.9	±3.6	±2.2	±0.1	±0.1	–	–	±1.1	±1.2	±0.6	–	–	–
2 (Healthy)	94.4	87.0	9.2	21.1	5.4	5.8	72.5	75.2	10.4	11.7	25.2	0.97	0.96	0.96
	±1.7	±1.5	±5.4	± 2.2	±0.3	±0.4	–	–	±2.5	±2.6	±7.7	–	–	–
3 (Healthy)	94.7	95.9	9.7	9.5	4.1	4.1	40.3	41.5	9.1	10.4	17.2	0.98	0.95	0.96
	±1.6	±2.1	±2.3	±1.0	±0.1	±0.2	–	–	±0.9	±1.7	±3.3	–	–	–
4 (Healthy)	93.3	92.1	20.3	20.3	4.1	3.9	49.8	48.3	8.8	12.0	15.1	0.98	0.96	0.96
	±1.4	±1.1	±1.8	±1.7	±0.1	±0.1	–	–	±1.1	±1.8	±2.9	–	–	–
5 (Stroke)	92.7	87.7	4.0	16.8	5.5	6.5	99.7	123.7	19.8	22.5	59.8	0.85	0.80	0.82
	±2.1	±2.3	±3.1	±1.8	±0.1	±0.2	–	–	±4.9	±6.5	±10.8	–	–	–

TABLE III: SA, EA, T, EI, NJ, CP Mean values and Root Mean Square Errors