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Postural control assessment via Microsoft Azure Kinect DK: An evaluation study

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ABSTRACT

Background and objective: Equipments generally used for entertainment, such as Microsoft Kinect, have been widely used for postural control as well. Such systems—compared to professional motion tracking systems—allow to obtain non-invasive and low-cost tracking. This makes them particularly suitable for the implementation of home rehabilitation systems. Microsoft has recently released a new version of Kinect, namely Azure Kinect DK, that is meant for developers, not consumers, and it has been specifically designed to implement professional applications. The hardware of this new version of the Kinect has been substantially improved as compared with previous versions. However, the accuracy of the Azure Kinect DK has not been evaluated yet in the context of the assessment of postural control as done for its predecessors.

Methods: We present a study to compare the motion traces of the Azure Kinect DK with those of a Vicon 3D system, typically considered the gold standard for high-accuracy motion tracking. The study involved 26 subjects performing specific functional reach and functional balance exercises.

Results: The results clearly indicates that the Azure Kinect DK provides a very accurate tracking of the main joints of the body for all the recording taken during the lateral reach movement. The Root Mean Square Error (RMSE) between the two tracking systems obtained is approximately 0.2 for the lateral and forward exercises while for the balance exercise it is around 0.47 considering the average of the results among all the joints. The angular Mean Absolute Error is approximately in the range 5–15 degrees for all the upper joints and independently on the exercise. The lower body joints show a higher angular error between the two systems. Not surprisingly, it was found that results are much better in correspondence of slow movements.

Conclusions: The results achieved that the Azure Kinect DK has an incredibly high potential to be used in applications of home rehabilitation, where the assessment of postural control is a fundamental and crucial activity.

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1. Introduction

People with motor disabilities see their ability to perform normal daily activities reduced, with a consequent loss of their independence. Performing repetitive exercises can help them overcome the limitations that result from their physical condition. Unfortunately, a study conducted with people with motor disabilities revealed that only 31% of the involved people does the exercises as recommended [1]. This results in a lower effectiveness of the treatment, and, therefore, in a possible deterioration of the patients' health. For this reason, it is necessary that a specialist—in this case, a physiotherapist—guides the patient in the correct execution of the exercises. However, such a scenario has a strong limitation. The patient must physically move to a rehabilitation centre and participate in a rehabilitation session.

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Table 1
Previous studies using Microsoft Kinect for computer assisted rehabilitation/physiotherapy or symptoms detection for motor-control related pathologies.

Reference	Year	Body focus	Gold standard	Objective	# Subjects
This work	2021	Full	Vicon x10+2	Postural control for the assessment of Azure Kinect DK	26
[6]	2021	NA	NA	Evaluation of the Azure Kinect and comparison with v1 and v2	0
[8]	2020	Full	Vicon x10	Gait analysis for the representation of diseases	5
[15]	2019	Full	Human & medical scale	Postural stability for Parkinson's disease motor symptoms	34
[16]	2019	Lower	Oqus 400 Qualisys medical AB	Estimation of the sagittal joint kinematics of children with cerebral palsy	18
[17]	2018	Lower	Oqus 400 Qualisys medical AB	Gait analysis is indicated in children with cerebral palsy	18
[18]	2016	Full	Elite motion capture system x6	Tracking clinical features for low back pain physiotherapy	12
[19]	2015	Full	PhaseSpace Impulse x8	Human pose tracking for comparing Kinect v2 and v1	10
[20]	2015	Lower	Optotrak Certus System	Gait analysis for representation of diseases	20

Motion tracking systems have been recently proposed to mitigate such a drawback by allowing the patient to do the exercises at home but in a controlled way. Such systems can track the movement of the patients, make them more involved, and guide them in the correct execution of the exercises. Also, they represent a non-invasive technology that can be used by patients who have difficulty holding physical devices. Last but not least, the technological evolution has drastically reduced the costs of motion tracking systems allowing the so-called VBI (Vision-Based Interaction) systems [2] to play a primary role in motor rehabilitation programs [3]. Also, low-cost equipments generally used for entertainment, such as the Nintendo Wii Remote Controller [4], the Microsoft Kinect and Kinect-2 [3], and the Intel RealSense camera [5] have provided promising results in the context of home rehabilitation. The advantage is that these devices do not use any marker or controller, and they allow to obtain a non-invasive and low-cost motion tracking systems.

In March 2020, Microsoft has released the latest version of the Kinect system, namely Azure Kinect DK[1] [2]. Despite the sensor has been specifically designed to enable applications not related to video games, to the best of our knowledge it has not been evaluated yet in the context of postural control, i.e., the preliminary and fundamental activity for any rehabilitation system [7].

Even if the Microsoft Azure Kinect DK has been recently compared to its predecessor Kinect V2 and the Vicon 3D system in the context of treadmill walking [8], the suitability of this new-generation motion capture system for home rehabilitation has not been evaluated yet. This paper aims at bridging this gap presenting a study aimed at comparing the accuracy of the Microsoft Azure Kinect DK to the Vicon 3D system[3]. This latter is largely considered the gold standard among motion capture systems for postural control [9–11]. The study involved 26 subjects and it was designed around two different tests widely used to assess postural control [12], such as the functional reach (FR) [13] and the functional balance (FB) tests [14]. Thus, the goal of this study is to demonstrate the validity of using the Azure Kinect in the tracking of these exercises to suggest the usability of such a sensor in a home setting for postural control. Despite some limitations emerged in cases of sudden and quick movements, especially for the lower part of the body, the results achieved indicate that Azure Kinect DK has great potential for rehabilitation applications involving postural control.

Contribution of the paper. Table 1 summaries related studies by considering different dimensions, i.e., year of publication, part of the body analyzed, gold standard used to evaluate the accuracy of the Kinect, the objective of the study, and the number of subjects involved in the experimentation. From the analysis of the table emerges that this paper reports the first empirical study aimed at evaluating both the real-time body tracking accuracy of Microsoft Azure Kinect DK as well as the applicability of such device for the assessment of postural control. Also, the number of involved subjects makes the study presented in this paper the second-largest study assessing the accuracy of the Kinect sensor in the context of computer-assisted rehabilitation/physiotherapy or symptoms detection for motor-control related pathologies.

2. Experimental method

The *goal* of this study is to evaluate the body tracking accuracy of the Microsoft Azure Kinect DK during sessions of postural control. The *perspective* concerns both with researchers who are interested in comparing the accuracy of Kinect to professional body tracking systems and with practitioners who are interested in evaluating the use of Microsoft Azure Kinect in professional software products in which the low cost is a more important non-functional requirement than the highest acquisition accuracy.

2.1. Context of the study

The context of the study is represented by 26 participants, 18 males and 8 females (see Table 2). Informed consent was obtained from all participants involved in the study. All participants declared to be healthy and the principles from the Declaration of Helsinki[4] were strictly respected.

The objects of the study are represented by two different body tracking systems, i.e., the Microsoft Azure Kinect DK and a Vicon 3D system, and three different exercises, i.e., lateral reach, frontal reach, and balance.

The study is steered by the following research questions:

- RQ_1: *Which is the **real-time body tracking accuracy**of Microsoft Azure Kinect DK as compared to the Vicon system in the context of **postural control**?*
- RQ_2: *Which is the **applicability**of Microsoft Azure Kinect DK for the **assessment of postural control**?*

The first research question aims at assessing the accuracy of Microsoft Azure Kinect in the context of postural control, while the second research question aims at evaluating its suitability in the context of home rehabilitation, where the assessment of the postural control plays a crucial role.

2.2. Experimental procedure

The environment stage (see Fig. 1) for the data acquisition was configured by allowing the best integration between the systems. The Microsoft Azure Kinect DK[5] was positioned outside the focal

[1] https://azure.microsoft.com/en-us/services/kinect-dk/
[2] A comparison between this newly released sensor and its predecessors is shown in the paper proposed by Tölgyessy et al. [6].
[3] https://www.vicon.com/
[4] https://www.wma.net/policies-post/wma-declaration-of-helsinki-ethical-principles-for-medical-research-involving-human-subjects/
[5] The automatic settings of the sensor were used. Specifically, the unbinned Nfov is the mode selected in this study. The resolution and the acquisition frequency are the parameters that most affect the quality of the acquisitions in relation to the

Table 2
Statistics of the participants.

	Num.	Age			Weight (kg)			Height (cm)		
		Mean	Median	Std. Dev.	Mean	Median	Std. Dev.	Mean	Median	Std. Dev.
Males	18	40	39	10	80.2	80.3	12.0	177.5	178.0	61.3
Females	8	32	33	4	62.8	60.6	17.2	162.0	163.0	76.7
Overall	26	38	34	9	74.8	73.8	15.7	172.8	175.0	97.7

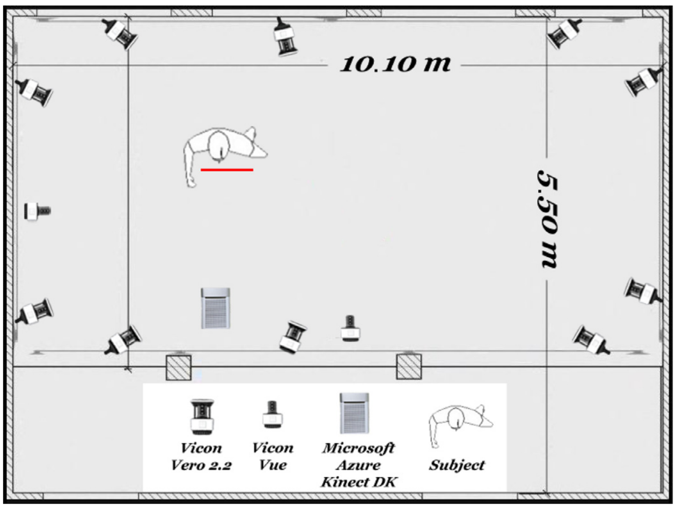

Fig. 1. The stage prepared for the data acquisition phase. The legend indicates the correspondence between the symbols and the sensors. The subject's position is reported as well.

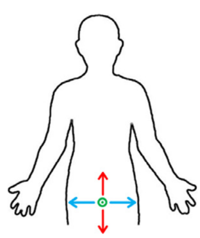

Fig. 2. The correspondence between each axis of the Vicon 3D systems and the recording of movements by the Microsoft Kinect Azure DK. The *x*-axis (green) of the Vicon 3D system corresponds to the optical axis of the Kinect camera, the *y*-axis (blue) corresponds to the lateral direction and the *z*-axis (red) to the plane orthogonal with respect to the ground. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

area of the 10 optometric Vicon Vero 2.2 cameras and without crossing the 2 Vicon FullHD Vicon Vue video cameras. The laboratory was equipped with six neon lamps equally distributed on two rows within the area where the exercises were carried out by the participants. Since there was no natural light, all the lamps were always lit during the execution of the experiments. No led lamps were added near the Azure sensor - as done in other works [5] - because the light in the Kinect area was considered sufficient.

The correspondence between the triaxial reference system of the proposed experiment and the movement of the subjects is depicted in Fig. 2.

The subjects were required to perform the exercises at a distance of approximately 2.5 meters (Fig. 1) from the Kinect Azure sensor. This distance is around the middle position of the limited range of the Kinect, as suggested by Su et al. [21].

speed of the movements. A higher resolution and acquisition frequency would allow a better detail. According to the official documentation, the unbinned Nfov mode is the one that allows the best compromise between these two characteristics.

To allow the placement of reflective markers on the body—39 markers, according to the *Marker sets for Plug-in Gait full body modelling* guidelines provided by the manufacturer[6]—the subjects were required to wear tight-fitting shorts and, depending on the gender, an upper-body garment (e.g., a sports bustier) or nothing. The *Marker placement for Plug-in Gait full-body model* establishes that the markers need to be placed on the head, arms, wrists, hands, trunk, pelvis, legs, and feet [22]. Due to the COVID-19 outbreak, all the participants also needed to wear a protective mask.

The subjects were asked to perform two kinds of exercises, as done in a previous study [12], i.e., Functional Reach (FR) and Functional Balance (FB). According to Weiner et al. [13], FR and FB offer a clinical measure of balance that is accurate, clinically relevant and easy to apply across a wide spectrum of physical activity.

FR aims at measuring the maximal distance one can reach forward/lateral beyond arm's length (in the horizontal plane), while maintaining a fixed base of support in the standing position [13]. The difference between the lateral and forward reach test relies on the reference axis: the mediolateral axis for the lateral movement and the focal for the forward exercise. As for the balance test, the subject was advised to stand as still as possible, while holding their eyes closed, on their favourite limb for 15 s.

All tests were performed three times aiming at collecting one recording for backup in case of technical errors (as done by Clark et al. [12]). Thus, each subject performed nine trials. Fig. 3 shows a photo taken during the experiment.

2.3. Data collection and pre-processing

Data were obtained from the Microsoft Kinect Azure using a Unity[7]-based application. A plugin[8] from the Unity asset store was adopted to embed the usage of the official Microsoft software development kit (SDK) specific for the Azure device. The data from the Vicon system were acquired through the Nexus 2.9.2 software.

Both Vicon and Kinect raw data have been filtered through a butterworth low-pass filter with a cut-off frequency set at 7.5 Hz, as suggested by Clark et al. [12]. The Vicon data were acquired at 100 fps by default, while the native frame sample frequency of the Kinect Azure device is irregular and close to 30 fps. Indeed, the official Azure documentation reports that the actual frame rate may vary slightly due to many reasons such as dropped data, a variation in the synchronization, the precision of the clock.[9]. Thus, a linear interpolation was applied to the Kinect data to create a constant sampling interval while maintaining time and frequency domain signal integrity [23]. Especially, the Kinect data has been interpolated using a moving mean filter where each mean is calculated over a sliding window of length equal to the Kinect FPS across neighbouring elements of the data. Also, due to the difference in the acquisition rate between the two systems, the Kinect data have been oversampled at 100 FPS. An example of such pre-processing is shown in Fig. 4.

[6] https://bit.ly/391uPxY
[7] https://unity.com/ (version 2019.4.1f1)
[8] https://bit.ly/2LnjY9a
[9] https://bit.ly/3in7z0w

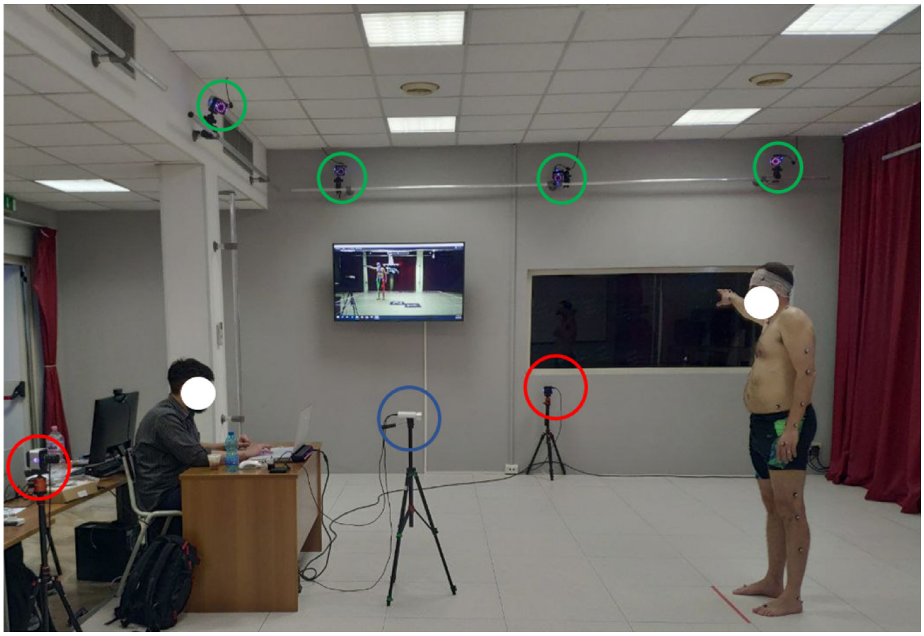

Fig. 3. A participant involved in the lateral reach exercise. The Microsoft Azure Kinect DK is circled in blue, the two Vicon video cameras are circled in red and 4 out of the 10 overall suspended optometric cameras are circled in green. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

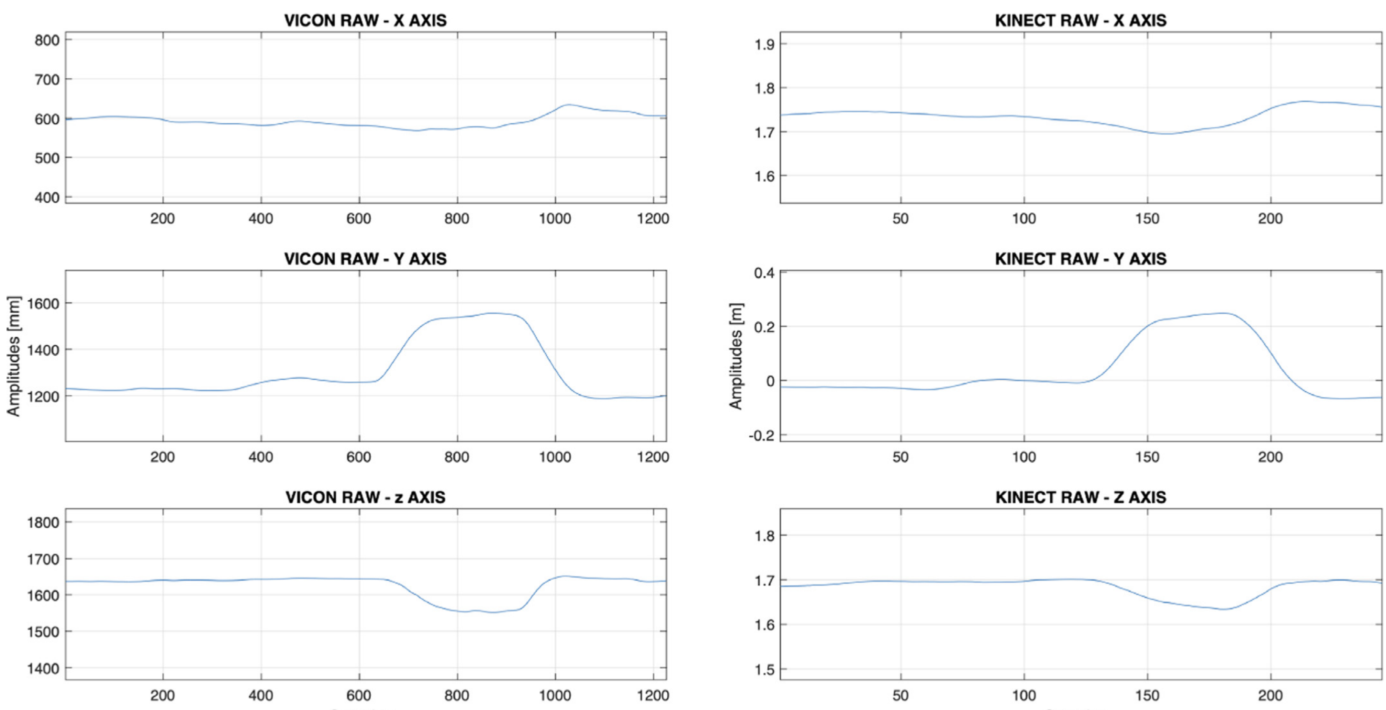

Fig. 4. On the left, the triaxial data for the head joint from the VICON system. On the right, from the Azure Kinect DK during a lateral reach exercise. The plotlines have been obtained by applying a low-pass and interpolation stages to the raw data.

The data acquired have been also submitted to a further synchronization phase to sharpen—at the best level possible—the signals correspondence in time and avoid any human errors inside the data[10]. This has been done by applying the cross-correlation algorithm. Indeed, when evaluating the cross-correlation between two signals, it is possible to obtain an estimation of the delay.[11] The result of this pre-processing stage can be seen in Fig. 5, where only the axis interested by the exercise movement has been

[10] The first level of synchronization in the acquisition between the systems has been manually performed by involving a third person who guided the subject and established the start and the end of each recording

[11] To provide a quantitative measure of the accuracy of the synchronization algorithm, a subset of the signals were extracted from the dataset and then the difference between the delay estimated by the cross-correlation technique and the real one (manually observed) were measured. Such an analysis revealed that the accuracy of the synchronization is 16.5 ± 12.2 frames.

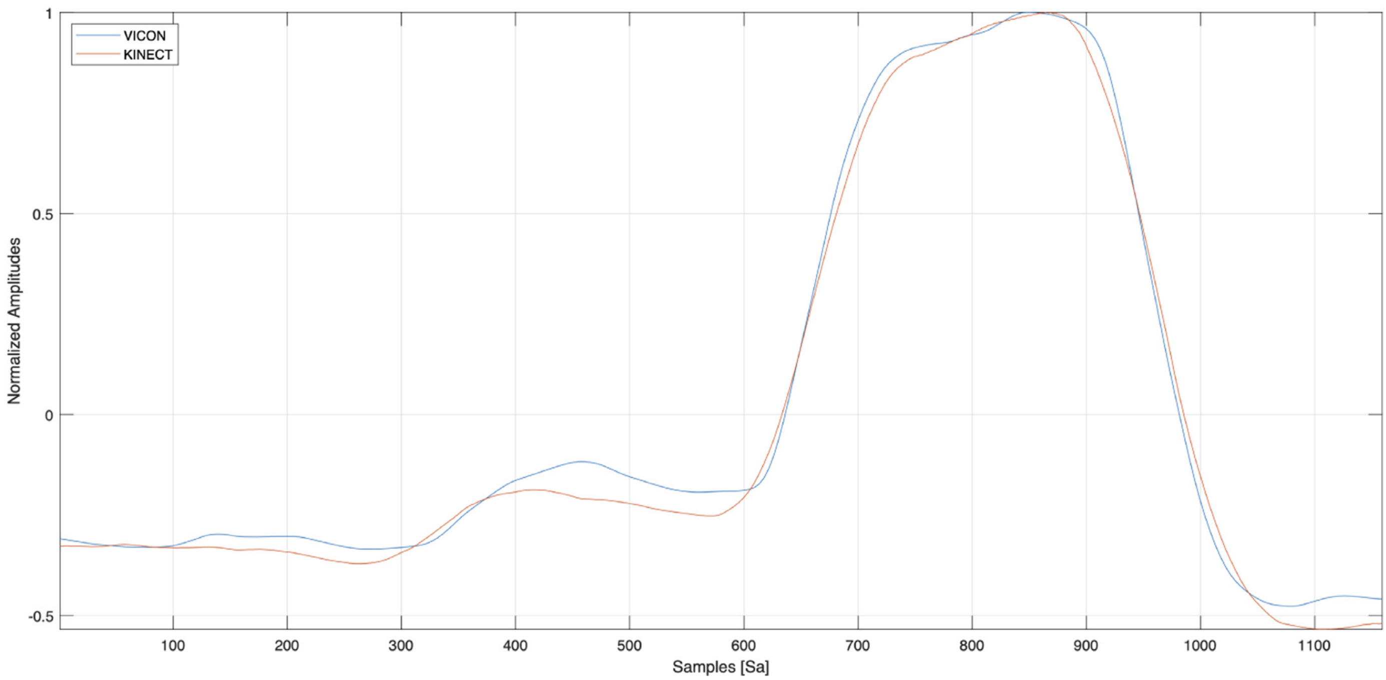

Fig. 5. The correspondence between the reference mediolateral axis during the tracking of the hand while the subject is involved in the lateral reach exercise. These signals have been further synchronized through the cross-correlation technique.

shown. Specifically, it regards the tracking of the hand joint in the mediolateral axis during the lateral reach exercise.

2.4. Data analysis

To answer the first research question (RQ_1), the capability of the Microsoft Azure Kinect DK to approximate—frame by frame—the Vicon tracking line was measured for different body joints and by varying the movements tracked. To perform this comparison, a common anatomical landmark reference was created by adapting the markers available in the Vicon system to the Kinect joints. This arrangement is more suitable because the Vicon system generates a greater number of markers trajectories compared to the Azure system. In this way, it was possible to approximate—in a precise way—a common anatomical reference for the joints taken into account.

Fig. 6 shows an example that highlights the virtual Azure Kinect joints, while the joint correspondences between Microsoft Azure Kinect DK and Vicon 3D can be observed in Fig. 7. A green circle indicates a Kinect reference joint, while a yellow circle represents a Vicon marker. In a few cases, it emerged the need to approximate the Vicon markers to generate a Vicon joint comparable to the Kinect one. The head, chest, and pelvis joints in the common anatomical landmark are the ones specified by the Azure Kinect sensor. These correspond to the green circle in Fig. 7. This kind of analysis has been undertaken for all the exercises. For the lateral and forward reach exercises, the comparison between the systems has been undertaken only with regard to upper body joints, while for the balancing exercise the tracking has been evaluated by considering joints all over the body.

Several metrics were used to assess the real-time body tracking accuracy of Microsoft Azure Kinect DK and the Vicon system. Given the two tracking curves, the Pearson correlation index and the difference between the two curves, i.e., tracking error, were computed. Then, the Root Mean Square Error (RMSE) was calculated.

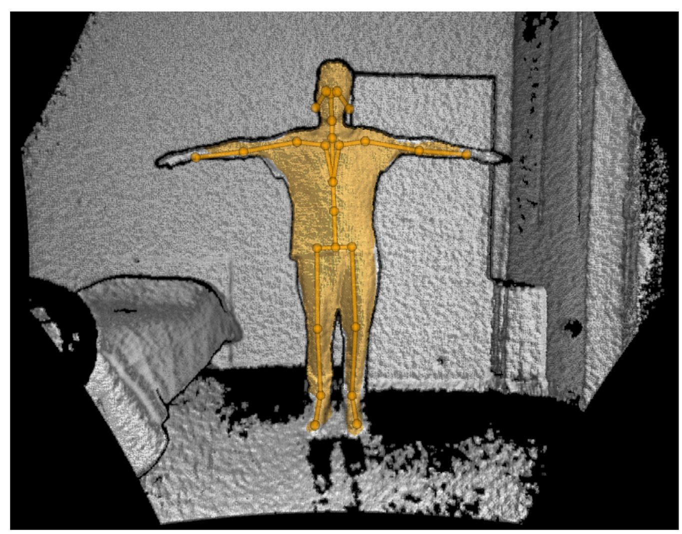

Fig. 6. The virtual joints calculated by the Azure Kinect superimposed to a human avatar.

To answer the second research question (RQ_2), a frame-wise comparison between the tracking of the Azure Kinect DK and the Vicon system was held in terms of angle difference. Such analysis was performed for various joints and each exercise. Angular values would be an important source of information for a physiotherapist to evaluate the effectiveness of an exercise and/or to identify specific pathologies. Thus, evaluating the accuracy of Microsoft Azure Kinect DK in such terms could be particularly useful to understand the applicability of such a device in the context of home rehabilitation.

The Mean Absolute Error (MAE) comparing the angles collected with the Kinect and the angles collected with the Vicon system was computed. The angles were computed frame-by-frame between each joint, i.e., the segment which links the origin of the

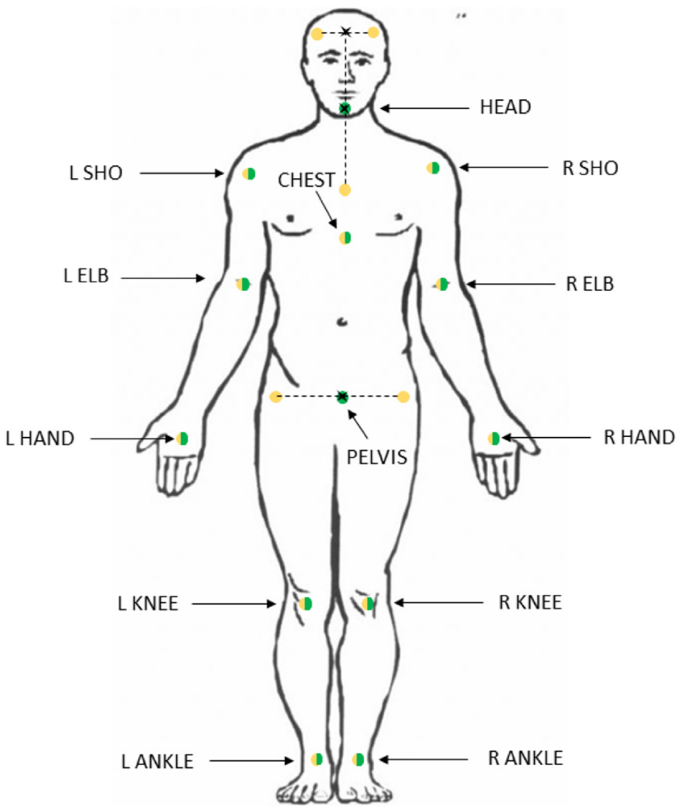

Fig. 7. Joint correspondences between Microsoft Azure Kinect DK and Vicon 3D. The green circles indicate the Kinect reference joints and the yellow circle the Vicon markers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

axis with the joint, and the reference axis, e.g., the mediolateral axis for the lateral reach exercise.

In details, for each joint, the angle between the axes with origin $[x_c, y_c, z_c]$ and the tri-axial coordinate $[x_p, y_p, z_p]$ given in every frame was evaluated. In this way, three angle measurements for the Kinect Azure and three reference angles for the Vicon were obtained. The angles were obtained by applying the following formulas:

$$\delta = \mathrm{atan}(\mathrm{sqrt}(((x_p - x_c)^2 + (y_p - y_c)^2)/((z_p - z_c)))$$

$$\alpha = \mathrm{atan}(\mathrm{sqrt}(((z_p - z_c)^2 + (y_p - y_c)^2)/(x_p - x_c)))$$

$$\beta = \mathrm{atan}(\mathrm{sqrt}(((x_p - x_c)^2 + (z_p - z_c)^2)/(y_p - y_c)))$$

The result is expressed in radians. The measurements were then converted in degrees using the atand Matlab function.

The two acquisition systems provide an offset due to the difference in the positioning of the tri-axial origin. This issue was considered and the offset was removed in order to obtain a fair comparison. Also, as shown in other works [5], this procedure allows to obtain more accurate results.

3. Analysis of the results

In this section, a discussion of the results is reported including the answers to the two research questions.[12]

[12] The raw data and full report of the results is available in the online appendix available at https://sites.google.com/view/2vitab-paper

3.1. RQ_1: comparison of Tracking accuracy

Fig. 8 shows the correlation indices (represented as bars) between the Kinect and Vicon tracking curves. The correlation has been measured for each joint and across the best two trials for all the three exercises.

In the first exercise, i.e., lateral reach, the results indicate that the Microsoft Kinect Azure tracking curves highly correlate with those of a professional system, i.e., Vicon 3D (first row in Fig. 8). Similar results have achieved for the second exercise, i.e., frontal reach (second row in Fig. 8). However, during this exercise—and, specifically, during a movement that insists on the focal axis of the Microsoft Azure Kinect DK—the pelvis joint shows a significant loss in terms of correlation with respect to the same tracking curve acquired with the Vicon system. This could be due to the setup of acquisition and the specific movement expected to be conducted during the frontal reach exercise. Indeed, an extension of the body in the focal axis of the Microsoft Kinect Azure DK may affect to hide the pelvis joint and therefore deteriorate the Azure's performances in tracking the pelvis. Regarding the third exercise, i.e., balance (third row in Fig. 8), the results indicate that sudden and quick movements—due to unpredictable and personal reaction of the subjects when losing the balance—across a full-body tracking do not allow the Kinect to accurately track the movements as compared to the Vicon system.

Fig. 9 shows the violin plots of the RMSEs obtained comparing the Kinect and Vicon tracking curves. The distributions of the RMSE values during the lateral reach and forward reach exercises are highly similar. This indicates that the performances of the Microsft Azure Kinect DK are strictly equal for a slow movement which insist both in the focal and in the mediolateral axis.

By looking at the means of each RMSE distribution for the lateral and forward reach, it is possible to see that it is lower or around 0.2 for all the considered joints referred to the upper body tracking. Fig. 10 compares the tracking lines of Azure Kinect DK and Vicon when the RMSE between them is approximately equal to 0.2. The tracking lines reported in the figure refer to the tri-axial tracking of the elbow during a forward reach exercise. The figure clearly shows that the tracking lines from the two devices are highly similar in terms of dynamics.

From the analysis of Fig. 9 it also emerges that the RMSE value—for some joints—during both lateral and frontal reach exercises exceeds 0.6 in few cases. Fig. 11 shows the tracking of the hand—along the three axes —during a later reach exercise. The plots show an episode of degradation of the tracking lines for around 50 Kinect frames for all the axis. This could refer to a loss during the tracking of the hand which has lasted approximately for two seconds. The interested segments have been bounded with red lines. The degradation of the tracking could be due to the occlusion of the arm by the hand relative to the sensor viewpoint. This scenario is probably caused by the use of only one Kinect sensor. A further reason could be the exit of the hand from the cone of the vision of the sensor. Indeed, another aspect that during the experimentation proved to be critical was the choice of the subject-sensor distance according to the height of the participant. A smaller distance, in fact, brings the hands closer to the limits of the frustum of the camera and involves an amplified perspective effect, which increases the probability that partial and total occlusions occur.

As for the balance exercise, Fig. 9 reports a different outcome. In this case, the means of the RMSE values across all the trials and for all the joints are equal to 0.54, 0.27, 0.34, 0.90, 0.47, 0.47 for the head, hand, knee, ankle, chest, and pelvis, respectively. This could be another clue that leads to the consideration that sudden and quick movements may affect the Kinect Azure DK motion capture capabilities.

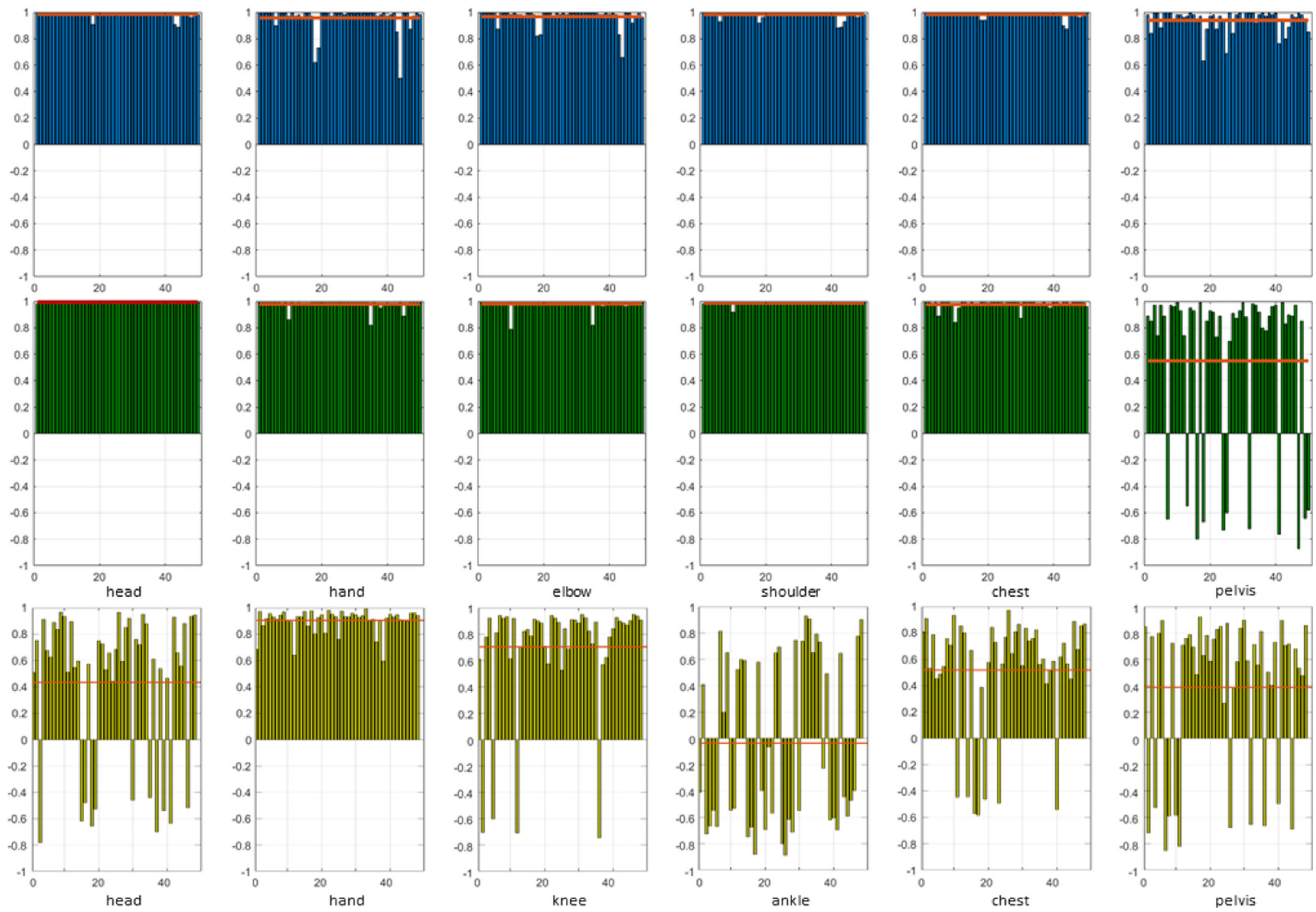

Fig. 8. The correlation indices obtained by comparing the Azure Kinect DK and Vicon tracking lines—with respect to the reference axis—for each specific joint during the lateral reach (blue bars), the forward reach (green bars) and balance (yellow bars) exercises. The analysis has been performed on the two best trials of all the subjects. The red lines indicate the mean. The first two plot rows refer to an upper body-tracking, while the third row shows plots related to full body joints. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. RQ_2: postural control with Microsoft Azure Kinect DK

Fig. 12 shows the violin plots of the Mean Absolute Error (MAE) obtained comparing the angles acquired by the Azure Kinect DK and the Vicon system.

From an overall perspective, it emerges that the violins on the left—the one related to the upper body tracking—appear thinner with respect to the right ones, related to the lower body joints. This provides evidence that for the upper body joints the Microsoft Azure Kinect DK can acquire the movement with a smaller angular error, while for the lower body joints the angular error increases.

For what concerns the lateral reach exercise, the angular MAE has a value generally smaller than 10 degrees for the upper body joints and between 10 and 15 degrees approximately for the lower body joints. The scenario is very similar also in the case of the forward reach exercise. Even with slight differences, also the violins from the balance exercise respect the error distribution resulted from the reach exercises.

4. Discussion and lesson learned

From the analysis of the results achieved, it is arguable that Microsoft Azure Kinect can be used in application of home rehabilitation for the assessment of postural control. The results clearly indicates that the Azure Kinect DK provides a very accurate tracking of the main joints of the body for all the recording taken during the lateral reach movement. Not surprisingly, it was found that results are much better in correspondence of slow movements.

It was also observed that the Azure Kinect DK—in few cases—may not return an accurate tracking of the pelvis joint during a functional reach test in the optical axis of the camera sensor. However, the main limitation found during the tracking comparison between the Azure Kinect DK and the Vicon 3D is related to quick movements. During the balance test, the sudden and fast reaction of the participants may have provided a not precise tracking of several joints.

The comparison with the Vicon 3D system was useful to assess the accuracy of the Azure Kinect with respect to a professional device that can be considered as a gold standard in the context of postural control. However, the Azure Kinect is the evolution of Kinect that has been previously used in the same context. Thus, it could be also interesting to understand the benefits provided by the Azure Kinect DK as compared to Kinect. Clark et al. [12] evaluated the Kinect using an experimental setting similar to the setting of the evaluation of this paper (also in this work only healthy participants were recruited). This allows us to compare the results of this study with the results achieved by Clark et al. [12]. Especially, a comparison between the Intraclass Correlation Coefficient (ICC) and the ratio Coefficient of Variation (CV) was evaluated. The ICC and the CV are two metrics of acquisition stability also reported

Fig. 9. Violin plot of the Root Mean Square Error for the body tracking analysis. The upper subplot refers to the joints tracked during the lateral reach exercise. The middle subplot shows the joints captured during the forward reach test while the lower subplot summarizes the data for the joints chosen for the balancing exercise. For some joints (e.g., the hand) it is intended the limb that has had the maximum extension, thus the limb chosen by the subject for the conduction of the exercise.

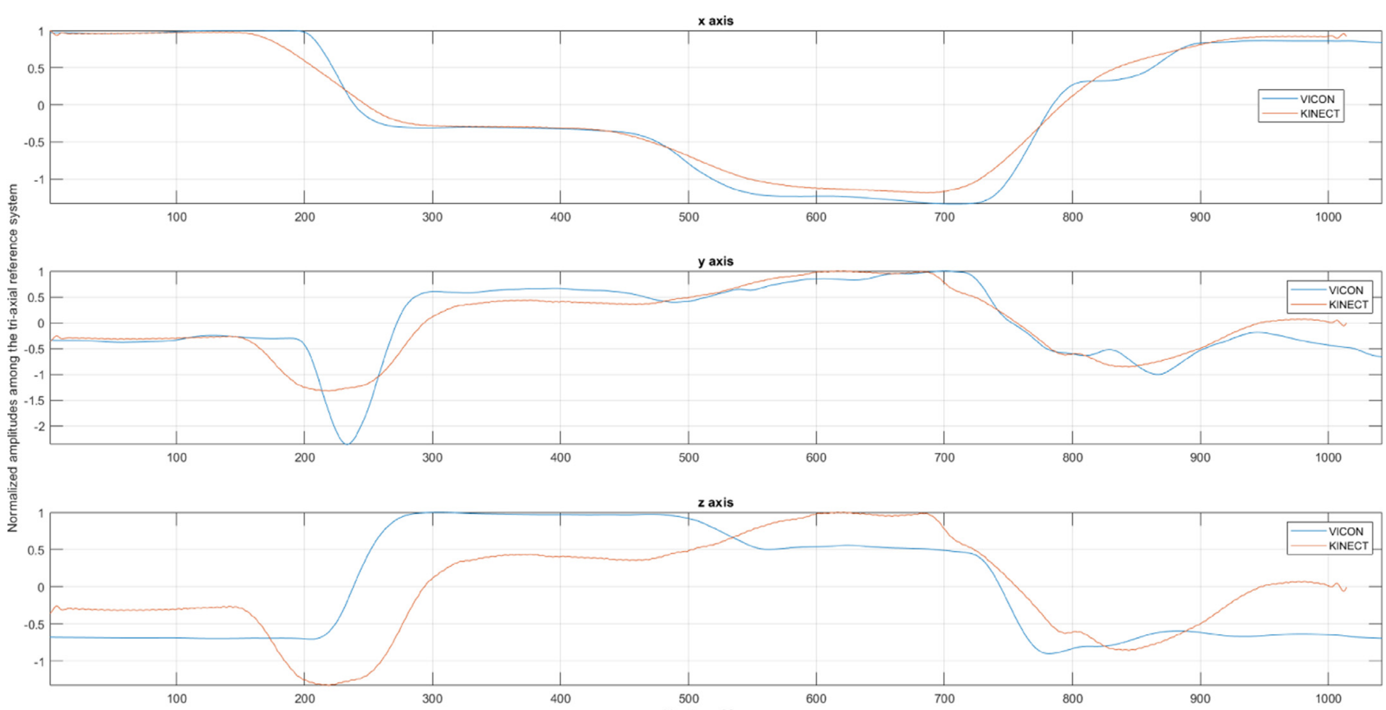

Fig. 10. Comparison of the tracking of the elbow—along the three axis—during a forward reach exercise (the reference axis for this exercise is the *y* axis). The RMSE obtained comparing the Kinect and Vicon tracking curves is approximately equal to mean RMSE achieved, i.e., 0.2.

by Clark et al. [12]. The ICC is particularly useful in applications where the assessment of consistency or reproducibility of quantitative measurement is made by different observer measuring the same quantity. The CV, instead, is a measure of relative variability and it is evaluated as the ratio of the standard deviation with respect to the the mean.

Table 3 reports the results achieved. The analysis was not performed for the functional balance since difficulties were found, reported by the subjects involved in the experiment, in managing the reactions to the loss of balance. With the objective of maintaining the balance, the subjects performed sudden and different movements. Therefore, measuring the stability across the differ-

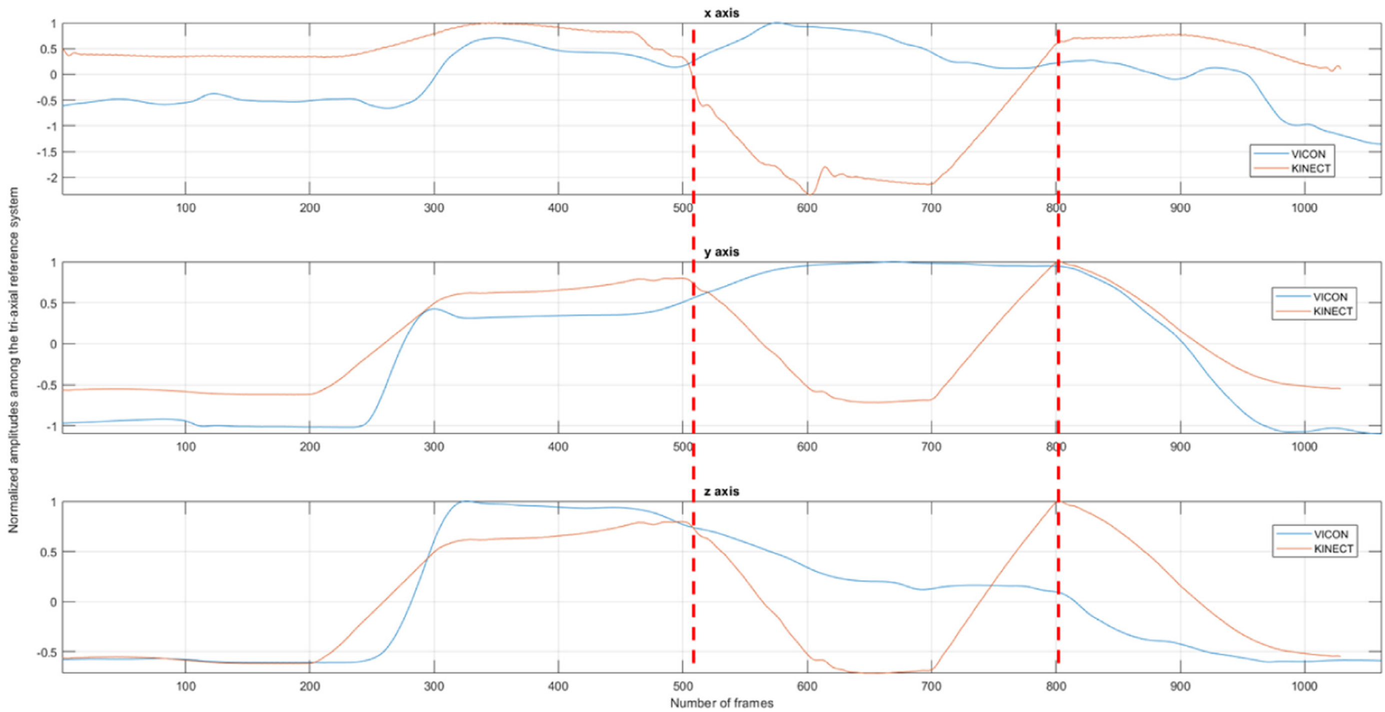

Fig. 11. Comparison of the tracking of the hand—along the three axis—during a forward reach exercise (the reference axis for this exercise is the y axis). The sections indicating degradation obtained during the tracking of the Kinect device have been bounded with dashed red lines.

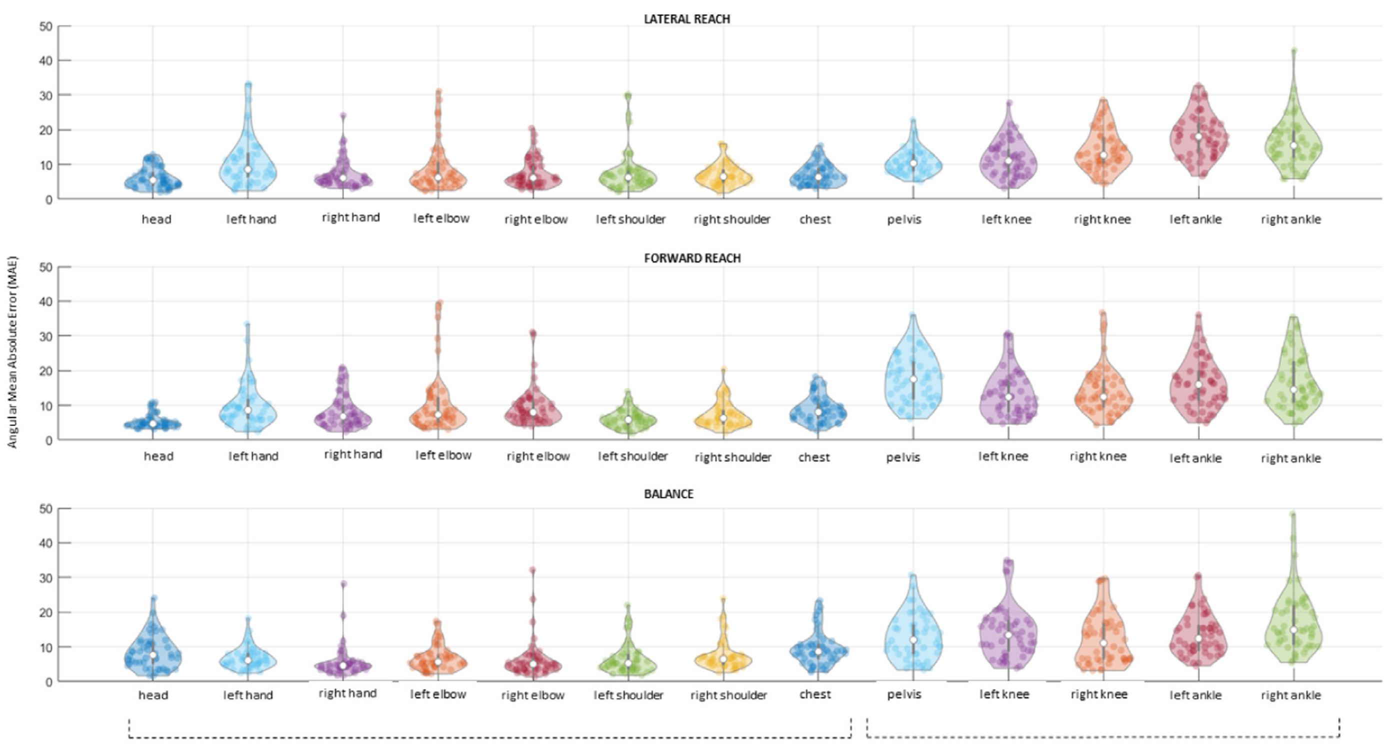

Fig. 12. Violin plot of the angular Mean Absolute Error (MAE) for the body tracking analysis. The upper subplot refers to the joints tracked during the lateral reach exercise, the middle subplot to the forward reach test, while the lower subplot summarizes the data for the balancing exercise.

ent trials does not make any sense because the movements are different.

One of the main results achieved is the systematic increasing of the ICC registered by the Azure Kinect DK system. The minimum ICC for the Azure Kinect DK is 0.94 and it refers to the displacement in millimeters of the hand joint during the lateral reach exercise. In this particular case, the ICC achieved by the Kinect is 0.73. Thus, an increase of 0.21 was registered for this specific joint. The same considerations also hold for the tracking of the hand in the forward reach exercise. Thus, a general improvement was observed in the reliability of the measure provided by the Azure Kinect DK system when tracking the hand of a subject. This result is partic-

Table 3
Comparison between Microsoft Kinect and Microsft Azure Kinect in terms of Intraclass Correlation Coefficient (ICC) and the ratio Coefficient of Variation (CV).

	Kinect [12]		Azure Kinect DK	
	$ICC_{2,1}$ (95% CI)	CV	$ICC_{2,1}$ (95% CI)	CV
Lateral Reach				
Sternum [mm]	0.89 (0.76–0.95)	6.3	0.98 (0.95–0.99)	0.41
Hand [mm]	0.73 (0.43–0.88)	12.3	0.94 (0.88–0.97)	0.10
Trunk [°]	0.87 (0.72–0.95)	7.8	0.95 (0.88–0.98)	0.20
Forward Reach				
Sternum [mm]	0.84 (0.65–0.93)	6.8	0.98 (0.98–1.00)	0.46
Hand [mm]	0.81 (0.59–0.92)	8.4	0.94 (0.86–0.97)	0.08
Trunk [°]	0.89 (0.76–0.95)	8.1	0.95 (0.90–0.98)	0.27

ular interesting because the tracking of the hand was a weakness of Kinect. As for the other joints, it was also observed an improvement for the space displacement of the sternum and the angular displacement of the trunk.

5. Conclusion

A study conducted to evaluate the motion capture capabilities of the newly released Azure Kinect DK was presented. The focus of the study was the assessment of postural control and the objective was to evaluate the accuracy of the Azure Kinect DK to advice the usage of such a device for this range of applications. The accuracy of Microsoft Azure Kinect DK was compared to a Vicon 3D system, a gold standard for high-accuracy motion tracking. The study involved 26 subjects performing functional reach and balance exercises. The results achieved provide a quantitative comparison respectively between (i) the Azure Kinect DK and the Vicon 3D system and (ii) the Azure Kinect DK and the previous version of the Microsoft Kinect, i.e., Kinect v2. The analysis of the results achieved reveals that the Azure Kinect DK has an incredibly high potential to be used in applications of home rehabilitation, where the assessment of postural control is a fundamental and crucial activity. The study also revealed some limitations that are summarized below:

- low quality movement tracking in case of fast movements;
- loss of tracking for movements along the focal axis (in case of single Kinect device);
- the subject-sensor distance should be carefully checked to avoid loss of tracking of body parts;

Future work will be devoted to replicate the experiment with a larger set of subjects. Also, other experiments considering different kinds of movements will be also planned to enlarge the analysis beyond the assessment of postural control. Last but not least, an array of Kinect will be also experimented to analyze the benefits as compared to a single device solution.

Declaration of Competing Interest

Authors declare that they have no conflict of interest.

CRediT authorship contribution statement

Mauro Antico: Funding acquisition. **Nicoletta Balletti:** Investigation, Resources, Data curation. **Gennaro Laudato:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Validation, Investigation, Data curation, Resources. **Aldo Lazich:** Investigation, Resources, Data curation. **Marco Notarantonio:** Investigation, Resources, Data curation. **Rocco Oliveto:** Conceptualization, Writing – review & editing, Methodology, Investigation, Supervision, Project administration. **Stefano Ricciardi:** Methodology, Writing – review & editing, Investigation. **Simone Scalabrino:** Formal analysis, Writing – review & editing, Validation. **Jonathan Simeone:** Software, Investigation, Data curation.

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