From Kinect™ to anatomically-correct motion modelling: Preliminary results for human application.

Bonnechère B.[1*], Sholukha V.[1], Moiseev F.[1], Rooze M.[1], Van Sint Jan S.[1]
[1] Laboratory of Anatomy, Biomechanics and Organogenesis (LABO), Université Libre de Bruxelles, CP 619, Lennik Street 808, 1070 Brussels, Belgium.
http://homepages.ulb.ac.be/~labo/
Corresponding author: bbonnech@ulb.ac.be

Abstract

The Kinect™ sensors can be used as cost effective and easy to use Markerless Motion Capture devices. Therefore a wide range of new potential applications are possible. Unfortunately, right now, the stick model skeleton provided by the Kinect™ is only composed of 20 points located approximately at the joint level of the subject which movements are being captured by the camera. This relatively limited amount of key points is limiting the use of such devices to relatively crude motion assessment. The field of motion analysis however is requesting more key points in order to represent motion according to clinical conventions based on so-called anatomical planes. To extend the possibility of the Kinect™ supplementary data must be added to the available standard skeleton. This paper presents a new Model-Based Approach (MBA) that has been specially developed for Kinect™ input based on previous validated anatomical and biomechanical studies performed by the authors. This approach allows real 3D motion analysis of complex movements respecting conventions expected in biomechanics and clinical motion analysis.

1 Introduction

Human motion tracking is widely used for movement analysis and biomechanical representation of the musculoskeletal system. Currently, most movement analysis laboratories are using Marker Based Systems (MBS) [1]. Although precision of this kind of device is high, practical problems still occur in daily practice: such systems are cumbersome and expensive, setting of the markers used on the subject is time-consuming and result validation is still an issue in the literature (reproducibility and accuracy issues). This can be explained by several factors. At first, markers need to be placed carefully on the subject's skin overlying some anatomical reliefs located underneath the skin surface, for example some bony tuberosities [2]. Errors during placement of the markers will induce errors during motion representation (i.e., based on the marker placement), and therefore result will show relatively low

B. Schouten et al. (eds.), *Games for Health*,
DOI 10.1007/978-3-658-02897-8_2,

reproducibility [3]. Motion artifacts caused by skin deformations can also reduce the measurement precision [4]. MarkerLess System (MLS) are developed for nearly twenty years and could represent alternatives for MBS [5-7]. MLS shows interesting perspectives for biomechanical applications: fast subject preparation because no marker placement, reduced reproducibility error due to the absence of marker placement. However, despite these promising advantages, MLS does not seem to have broad success in the motion analysis field. This lack of interest may be due to the fact that, in people's mind, MLS offers less precision than MBS. Let's note that MBS also show limitations: for example it is recognized that some skeleton motions (e.g., longitudinal rotations) are inducing limited skin displacements; marker displacements are therefore minimal. [8]. On the other hand, precision of MLS depends on the number of cameras used (single camera [9] to multiple cameras system [10]), types of algorithms (annealed particle filtering [11], stochastic propagation [12], silhouette contour [13], silhouette based techniques [14] …), estimation of whole body or only specific region.

The recent availability of the Kinect™ sensor - PrimeSense technology (Tel Aviv, Israel) [15-17] - a cost-effective, portable and single camera MLS, shows interesting perspectives in the revalidation and motion analysis field. Due to the high potential of the Kinect™ in various fields (e.g. motion assessment, rehabilitation, ergonomics…) research is being performed to estimate the precision and validity of this device for environment estimation [18], posture assessment [19] or full body analysis [20]. Currently, based on these studies, is appears that the Kinect™ can be used to assess some kind of motion in well-defined situations [21]. However these studies only focused on the validation of the crude stick model skeleton provided by the Kinect™ (with SDK) composed by 20 points. These 20 points are gross estimations of the center of the major joints of the human body (Figure 1). This kind of model however only allows simple motion assessment (e.g., vector angle between 3 points for knee or elbow flexion, simple geometric approach to estimate elbow abduction between shoulder and elbow…) with limited precision. Furthermore this skeleton is a planar representation of the human anatomy, and therefore does not really represent the human skeleton in 3 dimensions (3D). It must be stressed that in order to be used in clinics for the evaluation and the follow-up of patients, the standard provided skeleton must be improved to include anatomical knowledge to meet anatomical conventions. This paper presents a novel paradigm in motion analysis using a single Kinect™ sensor as MLS to collect raw data that are optimized thanks to Model Based Approached using past experimental data and knowledge collected by the authors.

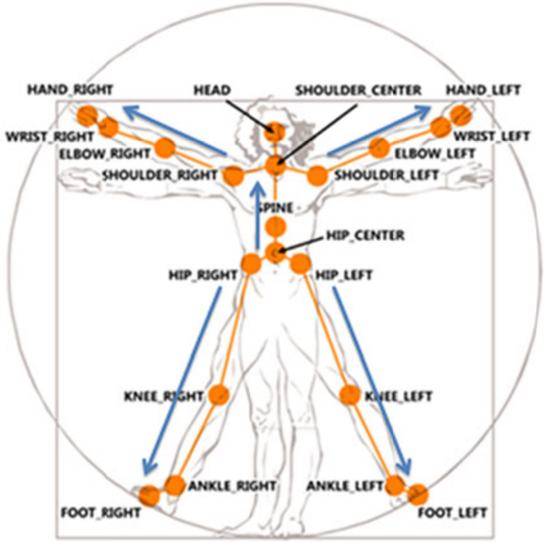

Figure 1: Stick model skeleton obtained with Kinect™ sensors and Kinect for Windows SDK (Source: **http://msdn.microsoft.com/en-us/library /jj131025.aspx)**

2 Methodology

Two main problems are met with the raw skeleton provides by the Kinect™: - the limited number of points available; - and the inconstant length between the successive points making the subject's segments. These inconsistencies lead to non-physiological results (Figure 2). The instability of the points is partly due to the fact that the segment lengths are not fixed during the motion causing important length variations when the subject is moving [22].

In order to tackle these problems, a model-based approach (MBA) was developed to enhance the anatomical accuracy of the standard skeleton obtained from the SDK associated to the Kinect™ input. Results lead to the availability of an enriched skeleton embedding supplementary anatomical data.

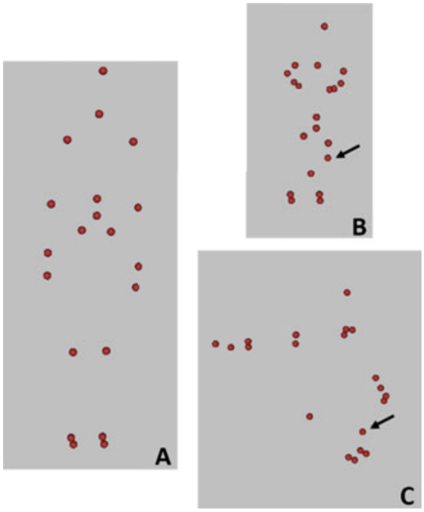

Figure 2: Example of miss tracking with Kinect™ sensor (before optimization). ***A*** Stick model diagram in upright position indicates that joint centres are well recognized (anterior view). ***B*** and ***C***. The subject is performing a deep squat movement (knee flexion), the arrow indicates that the left knee is miss tracked (***B***=anterior view, ***C***= lateral view).

Joint kinematics has been intensively studied these last 15 years in the author's department allowing a better understanding of joint behavior. Both in-vivo (e.g., study on living subject using MBS stereophotogrammetry for motion analysis) and in-vitro (e.g., study on cadaver using pins placed on the bone to record exact motions without soft tissues artifacts) studies were performed. All these knowledge were introduced into the developed MBA procedures in order to optimize the Kinect™ raw skeleton data (Figure 3).

The authors' past work on joint modeling was obtained from various techniques : 3D bones reconstructions obtained from medical imaging (CT scan) [23]; joint kinematic obtained with 6 DoFs instrumented spatial linkage [24], with embedded strain gages [25], with optoelectronic devices [26]; soft tissues information's were obtained from dissection or medical imaging [27].

Kinematic data available for each joint were assembled in one unique MBA pipeline in order to optimize skeletal segments characterized by some spatial poses (i.e., relative spatial orientation of the subject's segments during some movement). The new MBA algorithm is based on a previous double-step registration method developed within our group for the lower limb motion analysis [28].

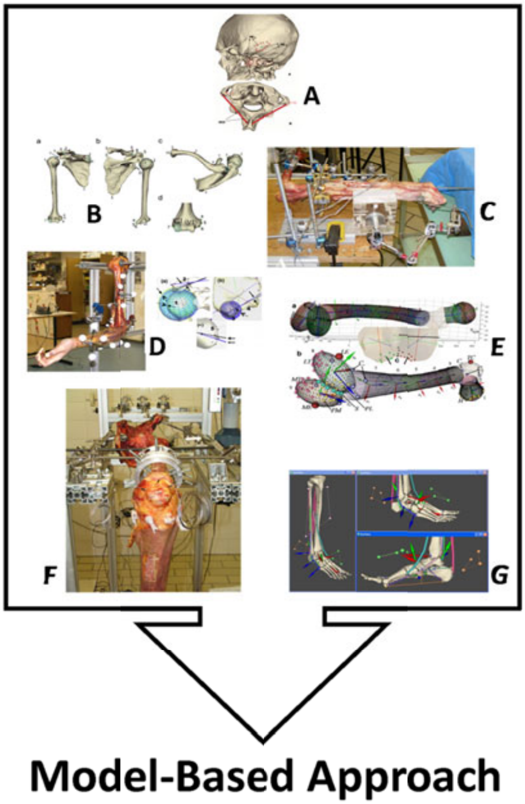

Figure 3: A few examples of biomechanical studies performed in the laboratory and implemented into MBA. ***A*** Musculoskeletal modelling and cervical spine kinematics [26,29]. ***B*** Shoulder rhythm (shoulder joint behaviour) [30-31]. ***C*** Hand, wrist and fingers biomechanics [32-34]. ***D***. Elbow (including soft tissues modeling) [35]. ***E*** Hip joint and femoral bone morphometry estimation [36]. ***F*** In-vitro knee joint kinematic [37-38]. ***G*** foot and ankle motion (in-vivo and in-vitro) [39].

MBA results are illustrated in Figure 4. MBA allows obtaining an enriched skeleton including supplementary anatomical landmarks that are necessary for motion representation according to anatomical and clinical conventions. The same procedure also rigidifies the subject's segment length. The output enriched skeleton is suitable for conventional motion analysis and further biomechanical analysis (for example, including soft tissue information based on the added anatomical landmarks).

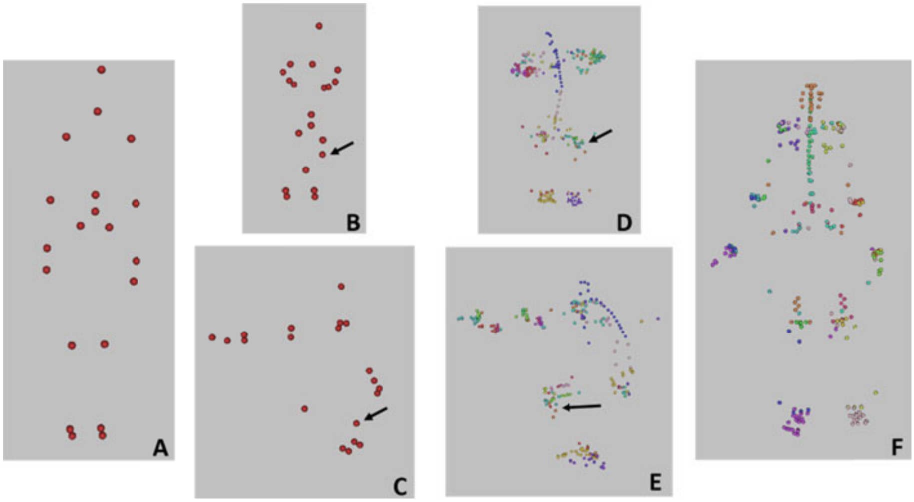

Figure 4: ***A, B, C*** Raw results (similar to Figure 2). Figures ***D*** and ***E*** show the same squat motion after MBA optimization process, arrows indicates that the left knee is in a more natural position. Figure ***F*** show the optimized skeleton in upright position. Note the supplementary anatomical data has been added to the raw data in order to obtain an enriched skeleton.

The enriched skeleton can then be fused with a generic anatomical skeleton model using data fusion methods based on spatial transformation [40]. Figure 5 is showing the full pipeline for an upper body motion analysis.

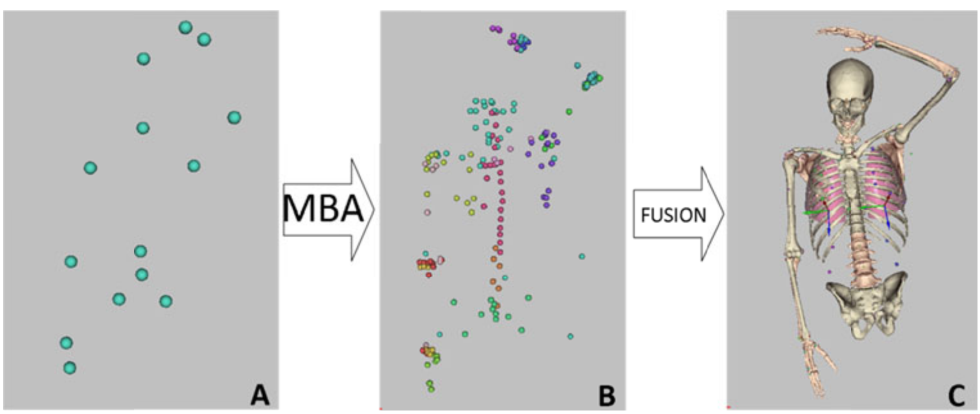

Figure 5: Example of complex 3D motion recorded with the Kinect™ and enriched with the presented MBA algorithm: conventional Hand-to-Head clinical assessment (called the Mallet Score [41]). ***A*:** raw results of the Kinect™ = input signal for MBA. ***B*:** optimized results = MBA output. ***C*:** MBA results fused with generic skeleton. Supplementary anatomical information, such as muscle or ligament information can be added to the skeleton.

3 Results

To assess results of the MBA method, 5 healthy subjects were equipped with reflective markers (Plug in Gait model) and were invited to realize clinical "Hand-to-Head", "Hand-to-Mouth" and "Hand-to-Back" motions (these motions are used to assess upper limb functions with patient suffering, for example, from obstetrical braxial plexus palsy [41], see Figure 5). Motion data were recorded with the Kinect™ and with a MBS (Vicon, 8MXT40s camera) simultaneously. Both signals were processed using MBA, and Range of Motions (ROM) were compared using Wilcoxon signed-rank test. Results are presented in Table 1

Table 1: Mean (std) ROM for the three studied motions, results are expressed in degrees.

	Hand-to-Head		Hand-to-Mouth		Hand-to-Back	
	Kinect™	MBS	Kinect™	MBS	Kinect™	MBS
Shoulder Flexion	35 (8)	33 (5)	29 (7)	30 (7)	32 (12)	29 (8)
Shoulder Abduction	75 (7)	69 (12)	22 (9)	19 (7)	18 (8)	18 (8)
Shoulder Rotation	60 (9)	53 (8)	19 (8)	14 (7)	35 (14)	29 (10)
Elbow Flexion	92 (9)	95 (11)	102 (20)	109 (18)	49 (16)	48 (14)
Forearm Prono-Supination	50 (12)	55 (16)	42 (14)	47 (20)	46 (16)	47 (19)

No statistical difference was found for both devices after processing the inputs with MBA. The (non-significative) differences were as following: shoulder flexion presented difference values from 3 to 10% depending on the motion, shoulder abduction from 0 to 13%, shoulder rotations from 11 to 26%, elbow flexion from 2 to 7% and forearm prono-supination from 2 to 11%.

4 Discussion

The Kinect™ seems promising not only for games purposes but also in clinics and rehabilitation. Raw skeleton data must however be processed prior to produce motion representation that are meaningful within clinical assessment activities. Research have already been performed allowing live visual feedback for patient correction during rehabilitation exercises [42], to assess the reachable volume with upper limb [43], to correct posture [44]. To the best of knowledge these studies are only using the simple stick model skeleton. Restrictions of the clinical use of the current system, prior to MBA optimization, include:

- The visual feedback is important to correct motion and increase benefits during rehabilitation [45]. One can easily imagine that the avatar used for visual feedback must be as close as possible to the real movement produced by the patient. Currently Kinect™ input can be used to animate avatar or models, but due to the lack of sufficient anatomical landmarks these avatars will not reflect the patient’s movements in an accurate way.
- Motion analysis is an important part of the clinical examination of patient suffering from various disorders such as neurological conditions (e.g. stroke, cerebral palsy, etc) or orthopaedic disorders (e.g. low back pain, total knee replacement, etc). This kind of examinations requires precise devices able to record 3D motions because these pathologies lead to complex motions patterns [46]. MLS must be adapted to be able to track such motion pattern.
- The same MBA approach could be used to gear human avatar controlled in gaming applications.

The presented MBA solves some of these problems thanks to various operations such as segment length rigidification, weighted smoothing for each particular joints and physiological joint behaviour based on joint mechanism obtained from experimental data. Precision of the overall skeleton is increased.

The MBA procedure can be used to animate a real skeleton as presented in Figure 5. MLS results were similar that those obtained with a MBS (Table 1). These results indicated that, for those particular motions, the combination of Kinect™ and MBA can be used to quantify complex 3D motion of the upper limb. It is important to note that, due to the important number of parameters of this model, calibration is required in order to have similar results that those provided with gold standard MBS. This calibration is mainly focusing on fine tuning of smoothing parameters, actually each joint can be configured separately. Despite the MBA some motions, in particular shoulder rotations, and the ankle joints, remain difficult to estimate and should be, therefore, carefully interpreted.

The enriched skeleton can also be integrated as Anatomical Optimization Engine within game environments in need of anatomical accuracy.

Further researches are needed to evaluate the possibilities of the Kinect™ for future potential clinical applications. This paper presented a method for fast and easy 3D motion analysis (kinematics evaluation). Currently there is a lack of tool easily available to clinicians to perform clinical motion assessment in a quick and efficient way. Proposed devices are either not precise or reproducible (e.g. goniometer) or expensive and with limited access (electrogoniometer, optoelectronic device). Bringing new and more accessible motion assessment devices could allow increasing the frequency of patient follow-up, and therefore would allow better patient monitoring.

New possibilities are also provided by the use of the skeletal model (Figure 5) obtained after the MBA process and after data fusion. Soft tissues (e.g. muscles, ligaments …) can be added to this model and information related to muscles behaviour during motion (muscle length, lever arm, etc) can be obtained. These new information could bring new insight on pathologies involving musculo-skeletal system such as spasticity [47]. Of course important validation works are required before going so far in the treatment of data obtained with this MBA.

5 Conclusion

Although the Kinect™ is already used for some limited clinical applications including basic motion assessment or live correction during rehabilitation, the underlying skeleton model is too crude for more advanced applications. This paper presents an optimization method that able to enrich the available raw data with supplementary anatomical and biomechanical information which were collected in previous scientific data collections. The optimization of the Kinect™ data with the proposed MBA method allows more accurate 3D motion analysis according to clinical conventions. Since the technology is cost-effective, not time-consuming to use and portable both patients and clinicians could benefit from this kind of developments thanks to an increase availability of motion assessment and better control of rehabilitation exercises. Note that this paper is using the first version of the Kinect™. The release of new Kinect™ hardware is expected to increase the quality of the MBA optimisation thanks to a better production of the raw skeleton.

6 Acknowledgments

This study has been funded through the ICT4Rehab project funded by the Brussels government (contract # 2010/PFS-ICT03).

7 References

1. Cappozzo A, Della Croce U, Leardini A, Chiari L. Human movement analysis using stereophotogrammetry. Part 1: theoretical background. Gait Posture. 2005 ;21(2):186-96
2. Cappozzo A, Catani F, Croce UD, Leardini A. Position and orientation in space of bones during movement: anatomical frame definition and determination. Clin Biomech. 1995 ;10(4):171-178

3. Ounpuu S, Davis R, DeLuca P. Joint Kinetics : methods, interpretation and treatment decision-making in children with cerebral pasly and myelomeningocele. Gait Posture 1996, 4 :62-78
4. Leardini A, Chiari L, Della Croce U, Cappozzo A. Human movement analysis using stereophotogrammetry. Part 3. Soft tissue artefact assessment and compensation. 2005 ;21(2):212-25
5. Rohr, K. Incremental recognition of pedestrians from image sequences. Proc. IEEE CVPR 1993; 8–13
6. Regh, J. M., and T. Kanade. Model-based tracking of selfoccluding articulated objects. Proc. IEEE CVPR 1995; 612–617
7. Gavrila, D. M., and L. S. Davis. Towards 3-D model-based tracking and recognition of human movement: A multi-view approach. In Proceedings of the International Workshop on Automatic Face and Gesture Recognition, Zurich, 1995
8. Cappozzo A, Catani F, Leardini A, Benedetti M, Della Croce U. Position and orientation in space of bones during movement: experimental artifacts. 1996, 11 :90-100
9. Wagg D, Nixon M. Automated markerless extraction of walking people using deformable contour models. Computer Animation and Virtual Worlds. 1996, 15 (3-4):399-406
10. Kakadiaris I, Metaxes D. 3D human body model acquisition from multiple view. Proc. IEEE CVPR 1995, 3: 618-623
11. Deutscher J, Blake A, Reid I. Articulated body motion capture by annealed particle filtering. Proc. IEEE CVPR 2000, 11: 941-944
12. Isard M, Blake A: Visual tracking by stochastic propagation of conditional density. 4th European Conference on Computer Vision:Cambridge, UK 1996:343-356
13. Legrand L, Marzani F, Dusserre L: A marker-free system for the analysis of movement disabilities. Medinfo 1998, 9(2):1066-1070
14. Cheung G, Baker S, Kanade T: Shape-from-silhouette of articulated objects and its use for human body kinematics estimation and motion capture. IEEE Conference on Computer Vision and Pattern Recognition: Madison, WI: IEEE 2003:77-84
15. Freedman, B., Shpunt, A., Machline, M., Arieli, Y., 2010. Depth Mapping Using Projected Patterns. 20100118123. Prime Sense Ltd., United States.
16. Shpunt, A., 2010. Depth Mapping Using Multi-beam Illumination. Prime Sense Ltd, United States. 20100020078.
17. Spektor, E., Mor, Z., Rais, D., 2010. Integrated Processor for 3D Mapping. Prime Sense Ltd, United States. 20100007717.
18. Dutta T. Evaluation of the Kinect™ sensor for 3-D kinematic measurement in the workplace. Appl Ergon. 2012; 43 (4): 645-9
19. Clark RA, Pua YH, Fortin K, Ritchie C, Webster KE et al. Validity of the Microsoft Kinect for assessment of postural control. Gait Posture.2012; 36(3): 372-7
20. Gabel M, Gilad-Bachrach R, Renshaw E, Schuster A. Full body gait analysis with Kinect. Conf Proc IEEE Eng Med Biol Soc. 2012 ;2012: 1964-7.
21. Lowes LP, Alfano LN, Yetter BA, Worthen-Chaudhari L, Hinchman W et al. Proof of concept of the ability of the kinect to quantify upper extremity function in dystrophinopathy. PLoS Curr. 2013 [Epub ahead of print]
22. Bonnechère B, Jansen B, Salvia P, Bouzahouene H, Omelina L, Cornelis J, Rooze M, Van Sint Jan S. What are the current limits of the Kinect sensor? In: ICDVRAT. Laval. France; 2012.

http://www.springer.com/978-3-658-02896-1

Games for Health
Proceedings of the 3rd european conference on gaming and playful interaction in health care
Schouten, B.; Fedtke, S.; Bekker, T.; Schijven, M.; Gekker, A. (Eds.)
2013, XI, 308 p. 83 illus., 70 illus. in color., Hardcover
ISBN: 978-3-658-02896-1