Clinical Biomechanics 24 (2009) 246–253

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Review

A framework for the definition of standardized protocols for measuring upper-extremity kinematics

A. Kontaxis [a], A.G. Cutti [b], G.R. Johnson [a], H.E.J. Veeger [c,d,*]

[a] Newcastle University, Newcastle upon Tyne, United Kingdom
[b] INAIL Prostheses Centre, Vigorso di Budrio, Italy
[c] VU University Amsterdam, Amsterdam, The Netherlands
[d] Delft University of Technology, Delft, The Netherlands

ARTICLE INFO

Article history:
Received 23 July 2008
Accepted 24 December 2008

Keywords:
Shoulder
Elbow
Kinematics
Framework
Standard

ABSTRACT

Background: Increasing interest in upper extremity biomechanics has led to closer investigations of both segment movements and detailed joint motion. Unfortunately, conceptual and practical differences in the motion analysis protocols used up to date reduce compatibility for post data and cross validation analysis and so weaken the body of knowledge. This difficulty highlights a need for standardised protocols, each addressing a set of questions of comparable content. The aim of this work is therefore to open a discussion and propose a flexible framework to support: (1) the definition of standardised protocols, (2) a standardised description of these protocols, and (3) the formulation of general recommendations.
Methods: Proposal of a framework for the definition of standardized protocols.
Findings: The framework is composed by two nested flowcharts. The first defines what a motion analysis *protocol* is by pointing out its role in a motion analysis *study*. The second flowchart describes the steps to build a protocol, which requires decisions on the joints or segments to be investigated and the description of their mechanical equivalent model, the definition of the anatomical or functional coordinate frames, the choice of marker or sensor configuration and the validity of their use, the definition of the activities to be measured and the refinements that can be applied to the final measurements. Finally, general recommendations are proposed for each of the steps based on the current literature, and open issues are highlighted for future investigation and standardisation.
Interpretation: Standardisation of motion analysis protocols is urgent. The proposed framework can guide this process through the rationalisation of the approach.

1. Introduction

In the past 20 years, quantitative motion analysis techniques have provided answers to a wide variety of problems concerning upper-extremity biomechanics. Moreover, different authors have addressed similar problems from different perspectives (Anglin and Wyss, 2000b). At this stage of development, one would expect, therefore, to be able to compare or integrate the results from different studies to draw stronger or broader conclusions. Unfortunately, this is not always possible, due to conceptual and practical differences in the motion analysis protocols used resulting in the application of different techniques or terminologies to define similar measurable quantities (Anglin and Wyss, 2000b). For instance, different authors used different kinematic models of the upper-limb (van der Helm, 1994b; Murray and Johnson, 2004), coordinate systems (Anglin and Wyss, 2000a; Cutti et al., 2008), motor tasks (Murray and Johnson, 2004, van Andel et al., 2008), scapula or clavicle tracking or optoelectronic marker setups (Johnson et al., 1993; Karduna et al, 2001; Ludewig et al., 2004; Anglin and Wyss, 2000a). This difficulty highlights a need for standardised protocols for motion analysis of the upper extremity.

Although it is almost impossible to define a single, universal protocol able to address all possible questions, at least a certain degree of standardisation should be sought. In particular, it should be possible to agree on general recommendations and to define standardised protocols, each addressing a set of questions of comparable content. The aim of this work is therefore to open a discussion and propose a flexible framework to support: (1) the definition of standardised protocols, (2) a standardised description of these protocols, and (3) the formulation of general recommendations. Through the framework, the authors aim to clear confusion regarding kinematics results obtained from anatomical and functional frames, as well as giving recommendations on how to use these

* Corresponding author. Address: VU University Amsterdam, Amsterdam, The Netherlands.
E-mail address: h_e_j_veeger@fbw.vu.nl (H.E.J. Veeger).

0268-0033/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.clinbiomech.2008.12.009

3. Discussion and conclusions

In this paper the authors have tried to summarise the essential steps to be addressed in the definition of motion analysis protocols focusing on (clinical) upper extremity kinematics. In addition, some basic recommendations have been formulated and open problems have been identified.

As stated in the introduction, the aim of this paper was not to define one single standardised protocol, but to provide guidelines for protocol developments, comparable to initiatives elsewhere (Bossuyt et al., 2003). Detailed protocols with specific recommendations will have to follow, to measure parameters useful to answer to questions of comparable content. These detailed standardised protocols should be easily developed following the proposed framework which was specifically developed to be both flexible (to adapt to different studies) and detailed in the content to clearly point out the steps required to define a protocol. Both in the framework and in the recommendations, we have tried to point out the difference between segment and joint kinematics, as well as the difference between anatomical and functional frames. This effort was motivated by the feeling of confusion regarding the meaning of the angle patterns obtained by decomposing the relative orientation of the anatomical frames of two adjacent segments. As already pointed out, the axes of anatomical frames are only rough approximations of the real joint axes of rotations. As a consequence, the angles may not closely follow the actual rotations of the joint. Only rotations obtained by decomposing the orientation around functional axes can give indications of the real joint rotations. The confusion that sometimes emerges can also be due to the terminology originally proposed in the ISB recommendations for "Joint Coordinate Systems". We think that efforts should be put in reviewing the terminology to enhance clarity. This appears even more urgent since the importance and the attention towards the estimation of functional frames will most probably increase in the next future, due to the diffusion of new measurement systems based in inertial sensors: these systems, in fact, are not (yet) able to measure the position of single anatomical landmarks, but only orientation.

By pointing out the essential steps for the definition of a protocol, we hope also to have clarified that a protocol definition is not merely related to "where to position sensors or markers on the body", but a much more complex task based on the definition of a kinematic model of the study objective.

Finally, we would like to identify the questions that, in the future, will require to be further discussed and addressed:

(1) the clear distinction between joint angles obtained from anatomical and functional frames;
(2) the formulation of guidelines for scapula tracking;
(3) the comparison of different set-ups for motion analysis;
(4) the problem of soft tissue artefact compensation.

Finally, the authors would reiterate that this paper should be seen as the basis for discussion in the research and clinical communities and eventually lead to an agreed set of protocols and standards.

Acknowledgments

The authors gratefully acknowledge the support of Michele Raggi, BEng, INAIL Prostheses Centre, in the preparation of the illustrations.

The authors would like to acknowledge the significant contribution to this aspect shoulder biomechanics made by the late Ingram Murray who died at the tragically young age of 35 in December 2008.

Appendix A

A.1. Building a technical, an anatomical, and a functional frame: application to the upper arm and to the Humerus (Fig. 6)

A.1.1. Describing a technical frame on the upper arm

Given three markers M_1, M_2 and M_3 attached on the skin of the upper arm, the TF can be constructed as follows:

$$Y_{TF} = M_2 - M_1/\|M_1 - M_2\|$$
$$Z_{TF} = Y_{TF} \wedge (M_1 - M_3)/\|X_{TF} \wedge (M_1 - M_3)\|$$
$$X_{TF} = Y_{TF} Z_{THX}$$

The above technical frame has an arbitrary alignment and it could have been defined using a different geometric rule. The markers though are placed in a high visibility position in order to maximise traceability.

A.1.2. Humeral anatomical frame (proximal)

Following the ISB recommendations (Wu et al., 2005) the anatomical frame H1 of the humerus is constructed based on the centre of rotation of the glenohumeral joint (GH) and the medial (EM) and lateral epicondyles (EM):

$$Y_{H1} = (\mathrm{GH} - E)/\|(\mathrm{GH} - E)\| : \text{longitudinal}$$
$$Z_{H1} = Y_{H1} \wedge (EM - EL)/\|Y_{H1} \ \wedge (\mathrm{EM} - \mathrm{EL})\| : \text{antero-posterior}$$
$$X_{H1} = (Y_{H1} \wedge Z_{H1})/\|\cdot\| : \text{medio-lateral}$$
$$E = (\mathrm{EL} + \mathrm{EM})/2$$
$$\mathrm{GH} = \text{Origin of the frame}$$

The axes of H1 can be used to describe both the glenohumeral joint rotations as well as the elbow joint rotations. While reasonable for the description of the GH joint kinematics, the use of Humeral AF (H1) for the elbow leads to a consisted kinematic cross-talk, which materializes in apparent rotations of the forearm, during pure Flexion–Extensions of the elbow (Cutti et al., 2006b)

A.1.3. Humeral functional frame (distal)

Following Cutti et al. (2008) the functional frame for the humerus, intended to describe the elbow Flexion–Extension, is constructed as follows:

$$X_{HD} = V_{FLEX}/\|V_{FLEX}\| : \text{lateral}$$
$$Z_{HD} = X_{HD} \wedge Y_{H1}/\|X_{HD} \wedge Y_{H1}\| : \text{posterior}$$
$$Y_{HD} = Z_{HD} \wedge X_{HD}/\|Z_{HD} \wedge X_{HD}\| : \text{cranial}$$

where V_{FLEX} is the mean Flexion–Extension axis of rotation of the elbow computed through the helical axis algorithm (Veeger et al., 1997), while Y_{H1} is the longitudinal anatomical axis of the humerus (see above). The use of this FF compared to the anatomical frame H1 minimises the kinematic cross-talk at the elbow joint.

References

Anglin, C., Wyss, U.P., 2000a. Arm motion and load analysis of sit-to-stand, stand-to-sit, cane walking and lifting. Clin. Biomech. 15 (6), 441–448.
Anglin, C., Wyss, U.P., 2000b. Review of arm motion analyses. Proc. Inst. Mech. Eng. [H.] 214 (5), 541–555.
Biryukova, E.V., Roby-Brami, A., Frolov, A.A., Mokhtari, M., 2000. Kinematics of human arm reconstructed from spatial tracking system recordings. J. Biomech. 33 (8), 985–995.
Borsa, P.A., Laudner, K.G., Sauers, E.L., 2008. Mobility and stability adaptations in the shoulder of the overhead athlete: a theoretical and evidence-based perspective. Sports Med. 38 (1), 17–36.
Bossuyt, P.M., Reitsma, J.B., Bruns, D.E., Gatsonis, C.A., Glasziou, P.P., Irwig, L.M., Lijmer, J.G., Moher, D., Rennie, D., de Vet, H.C., 2003. Towards complete and accurate reporting of studies of diagnostic accuracy: the STARD initiative. BMJ 326 (7379), 41–44.
Cappozzo, A., Catani, F., Leardini, A., Benedetti, M.G., Croce, U.D., 1996. Position and orientation in space of bones during movement: experimental artefacts. Clin. Biomech. 11 (2), 90–100.

Cappozzo, A., Della, C.U., Leardini, A., Chiari, L., 2005. Human movement analysis using stereophotogrammetry. Part 1: theoretical background.. Gait. Posture. 21 (2), 186–196.
Charlton, I.W., Johnson, G.R., 2006. A model for the prediction of the forces at the glenohumeral joint. Proc. Inst. Mech. Eng. 220 (8), 801–812.
Cutti, A.G., Cappello, A., Davalli, A., 2005a. A new technique for compensating the soft tissue artefact at the upper-arm: in vitro validation. J. Mech. Med. Biol. 5, 1–15.
Cutti, A.G., Paolini, G., Troncossi, M., Cappello, A., Davalli, A., 2005b. Soft tissue artefact assessment in humeral axial rotation. Gait. Posture 21 (3), 341–349.
Cutti, A.G., Cappello, A., Davalli, A., 2006a. In vivo validation of a new technique that compensates for soft tissue artefact in the upper-arm: preliminary results. Clin. Biomech. 21 (Suppl 1), S13–S19.
Cutti, A.G., Garofalo, P., Davalli, A., 2006b. How accurate is the estimation of elbow kinematics using ISB recommended joint coordinate systems? Gait Posture 24 (S2), S36–S37.
Cutti, A.G., Giovanardi, A., Rocchi, L., Davalli, A., Sacchetti, R., 2008. Ambulatory measurement of shoulder and elbow kinematics through inertial and magnetic sensors. Med. Biol. Eng. Comput. 46 (2), 169–178.
de Groot, J.H., Brand, R., 2001. A three-dimensional regression model of the shoulder rhythm. Clin. Biomech. 16 (9), 735–743.
Garofalo, P., Cutti, A.G., Filippi, M.V, Cavazza, S., Ferrari, A., Cappello, A., Davalli, A., 2009. Inter-operator reliability and prediction bands of a novel protocol to measure the coordinated movements of shoulder-girdle and humerus in clinical settings. Med. Biol. Eng. Comput., in press.
Johnson, G.R., Stuart, P.R., Mitchell, S., 1993. A method for the measurement of three dimensional scapular movement. Clin. Biomech. 8 (5), 269–273.
Karduna, A.R., McClure, P.W., Michener, L.A., Sennett, B., 2001. Dynamic measurements of three-dimensional scapular kinematics: a validation study. J. Biomech. Eng. 123 (2), 184–190.
Kontaxis, A., Banerjee, S., Bull, M.J.A., Johnson, G., 2007. Kinematics performance on activities of daily living after reverse shoulder joint replacement, in XXI ISB congress. J. Biomech., S108.
Kontaxis, A., Johnson, G.R., 2008. Adaptation of scapula lateral rotation after reverse anatomy shoulder replacement. Comput. Meth. Biomech. Biomed. Eng. 11 (1), 73–80.
Krumlinde-Sundholm, L., Holmefur, M., Kottorp, A., Eliasson, A.C., 2007. The Assisting Hand Assessment: current evidence of validity, reliability, and responsiveness to change. Dev. Med. Child Neurol. 49 (4), 259–264.
Ludewig, P.M., Behrens, S.A., Meyer, S.M., Spoden, S.M., Wilson, L.A., 2004. Three-dimensional clavicular motion during arm elevation: reliability and descriptive data. J. Orthop. Sports Phys. Ther. 34 (3), 140–149.
Marchese, S.S., Johnson, G.R., 2000. Measuring the kinematics of the clavicle". In: 6th International Symposium on the 3D Analysis of Human Movement, Cape Twon, S. Africa. pp. 37–40.
Mell, A.G., LaScalza, S., Guffey, P., Ray, J., Maciejewski, M., Carpenter, J.E., Hughes, R.E., 2005. Effect of rotator cuff pathology on shoulder rhythm. J. Should. Elbow Surg. 14 (1 Suppl. S), 58S–64S.
Meskers, C.G., van de Sande, M.A., de Groot, J.H., 2007. Comparison between tripod and skin-fixed recording of scapular motion. J. Biomech. 40 (4), 941–946.
Murray, I.A., Johnson, G.R., 2004. A study of the external forces and moments at the shoulder and elbow while performing every day tasks. Clin. Biomech. 19 (6), 586–594.
Peterson, B., Palmerud, G., 1996. Measurement of upper extremity orientation by video stereometry system. Med. Biol. Eng. Comput. 34 (2), 149–154.
Piazza, S.J., Cavanagh, P.R., 2000. Measurement of the screw-home motion of the knee is sensitive to errors in axis alignment. J. Biomech. 33 (8), 1029–1034.
Pronk, G.M., van der Helm, F.C., 1991. The palpator: an instrument for measuring the positions of bones in three dimensions. J. Med. Eng. Technol. 15 (1), 15–20.
Roux, E., Bouilland, S., Godillon-Maquinghen, A.P., Bouttens, D., 2002. Evaluation of the global optimisation method within the upper limb kinematics analysis. J. Biomech. 35 (9), 1279–1283.
Schmidt, R., sselhorst-Klug, C., Silny, J., Rau, G., 1999. A marker-based measurement procedure for unconstrained wrist and elbow motions. J. Biomech. 32 (6), 615–621.
Stokdijk, M., Biegstraaten, M., Ormel, W., de Boer, Y.A., Veeger, H.E., Rozing, P.M., 2000. Determining the optimal flexion-extension axis of the elbow in vivo - a study of interobserver and intraobserver reliability. J. Biomech. 33 (9), 1139–1145.
Teece, R.M., Lunden, J.B., Lloyd, A.S., Kaiser, A.P., Cieminski, C.J., Ludewig, P.M., 2008. Three-dimensional acromioclavicular joint motions during elevation of the arm. J. Orthop. Sports Phys. Ther. 38 (4), 181–190.
van Andel, C.J., Wolterbeek, N., Doorenbosch, C.A., Veeger, D.H., Harlaar, J., 2008. Complete 3D kinematics of upper extremity functional tasks. Gait. Posture 27 (1), 120–127.
van der Helm, F.C., 1994a. A finite element musculoskeletal model of the shoulder mechanism. J. Biomech. 27 (5), 551–569.
van der Helm, F.C., 1994b. Analysis of the kinematic and dynamic behavior of the shoulder mechanism. J. Biomech. 27 (5), 527–550.
Veeger, H.E., van der Helm, F.C.T., Rozendal, R.H., 1993. Orientation of the scapula in a simulated wheelchair push. Clin. Biomech. 8 (2), 59–111.
Veeger, H.E., Yu, B., An, K.N., Rozendal, R.H., 1997. Parameters for modeling the upper extremity. J. Biomech. 30 (6), 647–652.
Veeger, H.E., Magermans, D.J., Nagels, J., Chadwick, E.K., van der Helm, F.C., 2006. A kinematical analysis of the shoulder after arthroplasty during a hair combing task. Clin. Biomech. 21 (Suppl 1), S39–S44.
Wu, G., van der Helm, F.C., Veeger, H.E., Makhsous, M., Van, R.P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., Werner, F.W., Buchholz, B., 2005. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion–Part II: shoulder, elbow, wrist and hand. J. Biomech. 38 (5), 981–992.

Glossary

(1) Technical frame (TF): A TF is a coordinate system associated with a body segment. It has normally no repeatable reference to the morphology of the segment and as such has an arbitrary position and orientation with respect to the bone. The placement of markers or sensors that define a TF is usually such as to comply with technical requirement (e.g. minimise soft tissue artefact, enhance visibility and comfort, etc.). For optoelectronic systems a TF is usually constructed by using the instantaneous position of at least three non-aligned superficial markers associated with the bony segment, based on an arbitrary geometric rule. For other measurement systems, e.g. electromagnetic or inertial and magnetic, it is the local coordinate system of the sensor associated with the bony segment.

(2) Anatomical frame (AF): An AF is a coordinate system associated with a bony segment. The planes of an AF approximate the frontal, transverse and sagittal anatomical planes of its segment. Its axes (named anatomical axes), are only first-order approximations of the real axes of rotation of the joint(s) that the segment forms. As such, when anatomical axes are assumed to be the axes about which a joint rotates, the resultant joint kinematics can be substantially affected by kinematic cross-talk (Piazza and Cavanagh, 2000).For the upper limb there are recommendations (Wu et al., 2005) for the construction of AF using the position of three non-aligned anatomical landmarks associated with the bony segment. For the construction of the AF the anatomical landmarks are usually calibrated with respect to technical frames. Alternatively an AF can be constructed by a postural pose where an external frame coincides with the anatomical axes as they are described by the ISB.

(3) Functional frame (FF): A FF is a coordinate system associated with a segment and is specifically intended to describe the kinematics of a joint formed by the segment. The FF is based on at least one functional axis of rotation of the joint, expressed in a technical (or anatomical) frame associated with the segment.A functional axis of a joint is the axis of rotation of the distal and proximal segments that are forming the joint, when these are actively or passively rotated relative to each other. For a pure hinge joint, the functional axis coincides with the axis of the hinge. For an "almost hinge" joint (e.g. the elbow and the knee), the functional axis is assumed as the mean axis of rotation, computed from the joint instantaneous axes of rotation. For a ball and socket joint there are no preferential axes of rotation. However, if the distal segment is rotated in a constant plane, the functional axis is defined as the axis perpendicular to the plane of rotation. Functional axes can be computed through a number of algorithms. One of the most commonly used is that based on the estimation of Instantaneous Helical Axes which allows expression of the mean axis of rotation of the joint of interest in the technical (or anatomical) frame of the corresponding segment of interest.With the functional axis expressed in the technical (or anatomical) frame of the segment of interest, FF can then be constructed by (1) using a combination of more functional axes of rotation, or (2) use a combination of the functional and anatomical axes.When computing the kinematics of the joint, the functional axis is assumed to be the axis around which joint rotations occur. This minimises the kinematic cross-talk.