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Editorial

Human movement analysis: the soft tissue artefact issue

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This Special Issue of the Journal of Biomechanics reports an overview of the innovative research being conducted on a problem which every researcher reporting on the kinematics of humans and animals must cope with. The problem is rooted in our inability to directly observe the bones of our participants during the activities of interest and it represents a critical challenge since it is the motion of these underlying bones that is generally the nexus of our research.

We are most often forced to reconstruct the motion of bones using the recorded trajectories of markers placed on the skin, which, due to the interposed soft tissues, are not rigidly fixed to the underlying bones. The local mobility of these markers (now commonly referred to as soft tissue artefact, or STA) leads to errors that, in some cases, are of the same order of magnitude as the motions at the joints being investigated. This problem therefore puts at risk the validity of a significant body of research in the basic, clinical and applied sciences. It is also a problem that, until recently, has been neither fully understood nor considered, arguably overlooked, by many of us whose research is affected by it. With this Special Issue, we hope this scenario will change.

Up to the sixties of the last century, scientists reconstructed the movement of a stick model of the human locomotor system as projected on a 2-D space or, in rare cases, in the 3-D space. These models were activated by the trajectories of markers located on the skin surface, most of the time on points approximating the joint centres and recorded using optical systems so that a sort of virtual exoskeleton in motion could be reconstructed. With these models they described body segment motions and no observation of any inner structure was attempted. This all changed with a study on human locomotion carried out from 1945 to 1947 at the University of California with the aim of designing advanced lower limb substitutes (Eberhart, 1947). Relevant results reported on the rotation of the pelvis, femur, and tibia about their longitudinal axes during walking and, for the first time, we could legitimately talk of bone movement as opposed to body segment movement. To achieve this, however, cortical pins with markers affixed to them had to be inserted into the volunteer's bones, thus providing a rigid link between the object being recorded (the marker) and that of interest (the bone). In doing so Eberhart's team was acknowledging the fact that markers located on the skin surface were incapable of reliably tracking the small rotations of the underlying bones due to the interposed deformable tissues. Bresler and Frankel, who participated in that study, seemed, however, to underestimate the magnitude of this problem. In fact, they tracked skin-mounted markers in their historical work on joint kinetics during level walking (Bresler and Frankel, 1950), describing the movement of the skin over the bone as causing *"some slight error in location of the target"* (target now being commonly described as marker).

In the 1950s and 1960s, the development of endo- and arthro-prostheses, and of reconstructive orthopaedic surgery in general, made the acquisition of deeper knowledge concerning both the movement of bones and the mechanics of human joints paramount. John Paul, at the University of Glasgow, responded to this urgency by initiating his pioneering studies around 1965. He estimated bone movement during different locomotor tasks using skin mounted markers and cinecameras and was able to provide fundamental data concerning the muscular forces and hip loading (Paul, 1966, 1967, 1969). This seminal research is a milestone in the history of biomechanics, and, once again, the problem of the skin movement over the bones was identified but given limited importance. For instance, errors in the reconstructed hip joint centre coordinates around 3 mm were hypothesized and assumed to "*correspond to inaccuracies in measurement, movement of the skin marker* (located over the greater trochanter) *relative to the skeleton and distortions due to film processing or projector lens"* (Paul 1967). While Paul (1967) concentrated on the distortion of the lenses and on high frequency errors and their effect on time derivatives of position data, we know now that, as reported by a number of papers in this Special Issue, STA errors caused by those skin mounted markers were much larger.

An often cited paper by Spoor and Veldpaus, in 1980, reports on the first study aimed at optimising the estimate of the pose of a body using measured positions of point markers located on it. This important report provided a framework which is still used today for the analysis of movement using multiple skin markers per segment. Nevertheless, their statement *"Methods based on light photogrammetry of markers associated to bone are usually relatively accurate as compared to electro-goniometry"* (Spoor and Veldpaus, 1980) gives the impression that the STA problem was, again, underestimated. At that time, however, there seemed to be already an awareness of the importance of improving current practice. For example, Cappozzo, in 1984, while elaborating on the sets of markers that should be mounted on the body segments, states that the *"relative movement between markers and underlying bone due to soft tissue deformation"* should be regarded as a measurement "*artefact"* (Cappozzo, 1984). He then recommends that markers be positioned so that the above-mentioned relative movement "*should be minimal"*, without, however, quantifying the importance of the issue.

Awareness of what we today call soft tissue artefact (STA) was gained in the nineties. In Cappozzo (1991), in a section entitled "*Skin marker artefacts*", we read: "*A major source of error in the experimental procedures using optoelectronic systems is associated with the relative movement between skin markers and underlying bone. This displacement, which cannot be avoided, exhibits time histories with the same frequency content of those which describe the actual body segment movement*". This paper, besides reinforcing the concept that, while estimating bone pose, the above-mentioned marker local movements should be regarded as measurement artefacts, also provides a measure of their effect on the estimate of the trajectory of the centre of the femoral head during walking.

From that time on, several groups have measured the magnitude of the STA and tackled the problem of the minimization of its propagation to bone pose estimate. By the end of the nineties, the measurement of STA was initiated first using markers mounted on cortical or periosteum pins (Cappozzo et al., 1996; Fuller et al., 1997; Holden et al., 1997; Reinschmidt et al., 1997a; Reinschmidt et al., 1997b) and then using different medical imaging techniques (Maslen and Ackland, 1994; Sati et al., 1996; Tranberg and Karlsson, 1998). As for the STA compensation methods, several algorithms were developed addressing STA at single-body

(Andriacchi et al., 1998; Ball and Pierrynowski, 1998; Cappello et al., 1997; Cheze et al., 1995) or multibody (Lu and O'Connor, 1999) level.

More recently, further studies, comprehensively quoted and reviewed in the papers of this Special Issue, have been performed using the above-mentioned invasive methods, providing artefact-free bone movement and joint kinematics during a wider range of tasks, quantifying the STA effect on joint kinematics, determining its main characteristics, and creating models to help understand its nature. It is important to notice, however, that the resulting information is still incomplete and, until this Special Issue, not readily available to the community. In the last decade, more elaborate STA compensation methods, also quoted in this Special Issue, have been proposed, but, given the scarcity of artefact-free data, none of them could be comprehensively validated.

It is interesting to note that, in recent times, both the assessment of the STA and the development of compensation methods have moved from an individual marker displacement perspective towards considering the overall movement of the maker-cluster, by characterizing its geometrical transformation (Benoit et al., 2015; Dumas et al., 2014; Grimpampi et al., 2014), and focusing specifically on the rigid component (i.e., translation and rotation) of this transformation as the only artefact movement to be compensated for (Bonci et al., 2015; Dumas et al., 2015).

Despite the above-mentioned efforts, the problem is still regarded as having critical relevance for human movement analysis research: "*Probably the last great challenge for optical systems is in using computational techniques to compensate for soft tissue measurements*" (Baker, 2006). "*Despite the numerous solutions proposed, the objective of reliable estimation of 3D skeletal system kinematics using skin markers has not yet been satisfactorily achieved and greatly limits the contribution of human movement analysis to clinical practice and biomechanical research*" (Leardini et al., 2005).

Presently, STA, along with other less critical factors, still limits the possibility to reach the desired accuracy in various applications. Only in a limited number of clinical applications (e.g., cerebral palsy, adult brain injuries), there is evidence that the use of motion analysis applied to gait and combined with an expert clinical evaluation can modify or reinforce the clinical decision, influence the planning of orthopaedic surgery, and/or rehabilitation programs (Chang et al., 2006; Cook et al., 2003; Ferrarin et al., 2015; Lofterød et al., 2007; Wren et al., 2011; Wren et al., 2013). Similarly, STA has a negative impact when investigating injury mechanisms during dynamic motor tasks. For example, although studies using skin markers have provided clues that the combination of knee abduction and internal rotation is a potential risk for the anterior cruciate ligament (McLean et al., 1999; Shimokochi and Shultz 2008) and, similarly, that excessive inversion and internal rotation of the rearfoot may constitute a potential risk for lateral ankle ligaments (Hertel 2002, Gehring et al., 2013), the accuracy with which such angles are currently estimated is still not adequate with respect to the entailed range of motion (Benoit et al., 2006). Improving this accuracy would enable a re-evaluation and improved understanding of the underlying mechanisms. In summary, the generalisation and strengthening of the effective role of motion analysis in clinical practice and in other application areas requires the six degrees-of-freedom joint kinematics to be estimated with a much higher accuracy than is possible today.

During the *Seventh World Congress of Biomechanics*, held in Boston in 2014, a number of human movement analysts recognised the need to address this ongoing issue and established a working group aimed at its resolution (the *Soft-Tissue-Artefact-Propagation-Attenuation Group*; *STAPAG*). The founding idea was that such a challenging problem could only be solved through a solidarity pact among interested scientists willing to share competences and resources. This Special Issue of the Journal of Biomechanics is one of the products of this joint effort.

In the first part of this Special Issue, this solidarity is highlighted by a detailed report made possible by the contributions of the majority of the authors who have measured the STA using either pins inserted into bones or fluoroscopy. By providing their raw data, the characteristics of the STA at various joints are expounded upon since a detailed knowledge of the phenomenon is a prerequisite for the assessment of its negative effects and to devise methods that minimize these effects. Standardized metrics for the description of the STA are proposed and data samples for body segments of both the upper and lower extremities and for numerous motor tasks are provided (Cereatti et al., 2017). These data samples also include artefact-free joint kinematics for the validation of STA compensation methods. In other studies, the amplitude of the STA, either assessed as displacements of individual markers or as the translation and rotation of a maker-cluster, are analysed at the pelvis level for different hip joint angles (Camomilla et al., 2017), at the thigh and shank levels during treadmill gait (Barré et al., 2017) and cycling (Li et al., 2017), and at the clavicle, scapula and humerus levels during daily life and sports activities (Blache et al., 2017). The well-known relationship between STA and joint angles is observed for some of the marker-cluster geometrical transformations (not only rotations and translations but also homotheties and stretches) (Barré et al., 2017). At the same time the role of factors other than joint angles, e.g. muscle activation, are investigated, suggesting that further development of STA compensation methods may have to include not only kinematic constraints but also internal forces, especially during activities with varying loading conditions (Li et al., 2017). In Dumas et al. (2017) the local displacements of the skin markers are not analysed as artefacts to be compensated for, but are seen in their real nature and used to characterize the movement of the soft tissue masses relative to the bone (wobbling masses) and the relevant dynamic effects on the execution of a motor task. This contribution was included in the Special Issue in order to emphasize the double perspective through which the local movement of the skin markers may be seen.

In the second part of the Special Issue, the propagation of the STA to different outputs of motion analysis is investigated to highlight the importance and the consequences of the phenomenon. The effect of the STA on the estimate of the knee joint axes through functional calibration is analysed both experimentally (Sangeux et al., 2017) and analytically (De Rosario et al., 2017). Both studies confirm the effects of STA on knee angles for all functional calibration approaches, stating that no approach can be generally considered superior to others regarding the impact of STA. Different calibration approaches proved different sensitivities to the knee varus–valgus or internal–external rotation ranges of movement (Sangeux et al., 2017) and to different characteristics of the artefacts (De Rosario et al., 2017), calling for strategies to limit the negative effects of STA that are specific to the selected approach. As regards the accuracy of the kinetic quantities estimated through musculoskeletal models driven by stereophotogrammetric recordings of skin-mounted marker trajectories, STA can cause variations in some cases higher than 30%, but without significantly altering the overall pattern of joint kinetics and contact forces (Lamberto et al., 2017).

The third part of the Special Issue revises the kinematic models of the lower limb (Leardini et al., 2017) and upper limb joints (Duprey et al., 2017) used in multibody kinematics optimisation, a method which is becoming extensively used for STA compensation as expounded upon in the fourth part of the Issue. The evaluation of these methods is focused on the knee (Richard et al., 2017) and shoulder (Naaim et al., 2017) joints, assessing the efficacy of different joint models in improving the kinematics estimates using the artefact-free kinematics made available in the first paper of this Special Issue (Cereatti et al., 2017). Results in this third part lead to the conclusion that the joint models devised so far still do not represent a reliable solution to the STA issue, for none of the investigated joints. These models have shown to somehow help the reduction of the STA effects, but enhanced joint modelling approaches including personalisation and/or stochastic processes are required to take full advantage of the anatomical information.

While the previous parts of the Special Issue dealt with improving our understanding of STA through descriptive modelling approaches, the fourth part deals with the state of the art in STA compensation. Most of these methods were validated using the data provided in this Special Issue (Cereatti et al., 2017). By exploiting the continuum mechanics theory of Cosserat and least squares methods and using a large in vivo database, Solav et al. (2017) confirms the existence of time variant marker-clusters almost unaffected by STA and proposes criteria for the instantaneous non-invasive selection of them. Alternatively, the compensation entailed in using multibody kinematics optimisation is enhanced by the projection of the skin markers onto a selected axis of the local system of coordinates (i.e., the humerus longitudinal axis) to cancel the deleterious effect of STA on this degree-of-freedom, reducing by half the errors for humerus axial orientation (Begon et al., 2017). Multibody kinematics optimisation is also used in the context of musculoskeletal modeling: adaptive kinematic constraints are introduced to limit the impact of STA and obtain a more physiologically valid representation of joint kinematics and intersegmental moments during gait (Potvin et al., 2017). Using these constraints, physiologically consistent representations of knee joint kinematics during motions commonly associated with non-contact knee injuries were obtained and injury mechanisms reconsidered (Smale et al., 2017). Methods are also reported that exploit the potential of extended Kalman filters, either simultaneously tracking maker trajectories and external forces (Bonnet et al., 2017a) or embedding an STA mathematical model in the filter (Bonnet et al., 2017b). The former approach, although tested only for sagittal symmetric motor tasks, may reduce up to one-third the STA effects on the reconstructed ground reaction forces and moments and, by inference, on intersegmental loads (Bonnet et al., 2017a). This approach also allows for a reduced error in joint kinematics, with the exception of degrees of freedom that undergo moderate displacements (Bonnet et al., 2017b).

And finally, the fifth part of the Special Issue addresses the emerging use of ultrasound techniques for the assessment and compensation of the STA (Jia et al., 2017; Masum et al., 2017).

Advanced optical motion capture systems have never been more affordable and accessible. The obvious question, with this compilation of STA-related research is this, however: can we now reliably and validly represent bone and joint motions using markers placed on the skin? The answer is that we are closer than fifteen years ago, but the light at the end of the tunnel cannot be seen yet. The papers in this Special Issue are nevertheless laying the tracks needed to reach this light. They bring together different approaches and points of view, facilitating a structured debate to devise future developments and provide knowledge, suggestions, and data that may accelerate the achievement of the ultimate goal of enhancing the accuracy of human and animal motion analysis performed using stereophotogrammetry and markers attached to the skin.

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References

Andriacchi, T.P., Alexander, E.J., Toney, M.K., Dyrby, C., Sum, J., 1998. A point cluster method for in vivo motion analysis: applied to a study of knee kinematics. Journal of Biomechanical Engineering 120, 743-749.

Baker, R., 2006. Gait analysis methods in rehabilitation. Journal of NeuroEngineering and Rehabilitation 3, 4-4.

Ball, K.A., Pierrynowski, M.R., 1998. Modeling of the pliant surfaces of the thigh and leg during gait. SPIE Proceedings Series 3254, 435-446.

Barré, A., Aissaoui, R., Aminian, K., Dumas, R., 2017. Assessment of the lower limb soft tissue artefact at marker-cluster level with a high-density marker set during walking. Journal of Biomechanics, doi:10.1016/j.jbiomech.2017.04.036.

Begon, M., Bélaise, C., Naaim, A., Lundberg, A., Chèze, L., 2017. Multibody kinematics optimization with marker projection improves the accuracy of the humerus rotational kinematics. Journal of Biomechanics, doi:10.1016/j.jbiomech.2016.09.046.

Benoit, D.L., Ramseym D.K., Lamontagne, M., Xu, L., Wretenberg, P., Renström, P., 2006. Effect of skin movement artifact on knee kinematics during gait and cutting motions measured in vivo. Gait & Posture 24, 152-64.

Benoit, D.L., Damsgaard, M., Andersen, M.S., 2015. Surface marker cluster translation, rotation, scaling and deformation: Their contribution to soft tissue artefact and impact on knee joint kinematics. Journal of Biomechanics 48, 2124-2129.

Blache, Y., Dumas, R., Lundberg, A., Begon, M., 2017. Main component of soft tissue artifact of the upper-limbs with respect to different functional, daily life and sports movements. Journal of Biomechanics, doi:10.1016/j.jbiomech.2016.10.019.

Bonci, T., Camomilla, V., Dumas, R., Chèze, L., Cappozzo, A., 2015. Rigid and non-rigid geometrical transformations of a marker-cluster and their impact on bone-pose estimation. Journal of Biomechanics 48, 4166-4172.

Bonnet, V., Dumas, R., Cappozzo, A., Joukov, V., Daune, G., Kulić, D., Fraisse, P., Andary, S., Venture, G., 2017a. A constrained extended Kalman filter for the optimal estimate of kinematics and kinetics of a sagittal symmetric exercise. Journal of Biomechanics, doi:10.1016/j.jbiomech.2016.12.027.

Bonnet, V., Richard, V., Camomilla, V., Venture, G., Cappozzo, A., Dumas, R., 2017b. Joint kinematics estimation using a multi-body kinematics optimisation and an extended Kalman filter, and embedding a soft tissue artefact model. Journal of Biomechanics, doi: 10.1016/j.jbiomech.2017.04.033.

Bresler, B., Frankel, J:P: (1950) The forces and moments in the leg during level walking. Transactions of the American Society of Mechanical Engineers 72, 27-36.

Camomilla, V., Bonci, T., Cappozzo, A., 2017. Soft tissue displacement over pelvic anatomical landmarks during 3-D hip movements. Journal of Biomechanics, doi:10.1016/j.jbiomech.2017.01.01 .

Cappello, A., Cappozzo, A., La Palombara, P.F., Lucchetti, L., Leardini, A., 1997. Multiple anatomical landmark calibration for optimal bone pose estimation. Human Movement Science 16, 259-274.

Cappozzo, A., 1984. Gait analysis methodology. Human Movement Science 3, 27-50.

Cappozzo, A., 1991. Three-dimensional analysis of human walking: Experimental methods and associated artifacts. Human Movement Science 10, 589-602.

Cappozzo, A., Catani, F., Leardini, A., Benedetti, M.G., Croce, U.D., 1996. Position and orientation in space of bones during movement: experimental artefacts. Clinical Biomechanics 11, 90-100.

Cereatti, A., Bonci, T., Akbarshahi, M., Aminian, K., Barré, A., Begon, M., Benoit, D.L., Charbonnier, C., Dal Maso, F., Fantozzi, S., Lin, C.-C., Lu, T.-W., Pandy, M.G., Stagni, R., van den Bogert, A.J., Camomilla, V., 2017. Standardization proposal of soft tissue artefact description for data sharing in human motion measurements. Journal of Biomechanics, doi:10.1016/j.jbiomech.2017.02.004.

Chang, F.M., Seidl, A.J., Muthusamy, K., Meininger, A.K., Carollo, J.J., 2006. Effectiveness of instrumented gait analysis in children with cerebral palsy - comparison of outcomes. Journal of Pediatric Orthopaedics 26, 612-616.

Cheze, L., Fregly, B.J., Dimnet, J., 1995. A solidification procedure to facilitate kinematic analyses based on video system data. Journal of Biomechanics 28, 879-884.

Cook, R.E., Schneider, I., Hazlewood, M.E., Hillman, S.J., Robb, J.E., 2003. Gait analysis alters decision making in cerebral palsy. Journal of Pediatric Orthopaedics 23, 292-295.

De Rosario, H., Page, Á., Besa, A., 2017. Analytical study of the effects of soft tissue artefacts on functional techniques to define axes of rotation. Journal of Biomechanics, doi:10.1016/j.jbiomech.2017.01.046 .

Dumas, R., Camomilla, V., Bonci, T., Cheze, L., Cappozzo, A. 2015. What portion of the soft tissue artefact requires compensation when estimating joint kinematics? Journal of Biomechanical Engineering 137(6), 064502.

Dumas, R., Camomilla, V., Bonci, T., Cheze, L., Cappozzo A., 2014. Generalized mathematical representation of the soft tissue artefact. Journal of Biomechanics 47, 476-81.

Dumas, R., Jacquelin, E., 2017. Stiffness of wobbling mass models analysed by a smooth orthogonal decomposition of the skin movement relative to the underlying bone. Journal of Biomechanics, doi:10.1016/j.jbiomech.2017.06.002.

Duprey, S., Naaim, A., Moissenet, F., Begon, M., Chèze, L., 2017. Kinematic models of the upper limb joints for multibody kinematics optimisation: An overview. Journal of Biomechanics, doi:10.1016/j.jbiomech.2016.12.005.

Eberhart, H.D., 1947. Fundamental studies of human locomotion and other information relating to design of artificial limbs. Prosthetic Devices Research Report. University of California, Berkeley.

Ferrarin, M., Rabuffetti, M., Bacchini, M., Casiraghi, A., Castagna, A., Pizzi, A., Montesano, A., 2015. Does gait analysis change clinical decision-making in post-stroke patients? Results from a pragmatic prospective observational study. European Journal of Physical and Rehabilitation Medicine 51, 171-184.

Fuller, J., Liu, L.J., Murphy, M.C., Mann, R.W., 1997. A comparison of lower-extremity skeletal kinematics measured using skin- and pin-mounted markers. Human Movement Science 16, 219-242.

Gehring, D., Wissler, S., Mornieux, G., Gollhofer, A., 2013. How to sprain your ankle – a biomechanical case report of an inversion trauma. Journal of Biomechanics 46, 175-178.

Grimpampi, E., Camomilla, V., Cereatti, A., de Leva, P., Cappozzo, A., 2014. Metrics for Describing Soft-Tissue Artefact and Its Effect on Pose, Size, and Shape of Marker Clusters. IEEE Transactions on Biomedical Engineering 61, 362-367.

Hertel, J., 2002. Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability. Journal of Athletic Training 37, 364-375.

Holden, J.P., Orsini, J.A., Siegel, K.L., Kepple, T.M., Gerber, L.H., Stanhope, S.J., 1997. Surface movement errors in shank kinematics and knee kinetics during gait. Gait & Posture 5, 217-227.

Jia, R., Monk, P., Murray, D., Noble, J.A., Mellon, S., 2017. CAT & MAUS: A novel system for true dynamic motion measurement of underlying bony structures with compensation for soft tissue movement. Journal of Biomechanics, doi:10.1016/j.jbiomech.2017.04.015.

Lamberto, G., Martelli, S., Cappozzo, A., Mazzà, C., 2017. To what extent is joint and muscle mechanics predicted by musculoskeletal models sensitive to soft tissue artefacts? Journal of Biomechanics, doi:10.1016/j.jbiomech.2016.07.042.

Leardini, A., Chiari, L., Croce, U.D., Cappozzo, A., 2005. Human movement analysis using stereophotogrammetry: Part 3. Soft tissue artifact assessment and compensation. Gait & Posture 21, 212-225.

Leardini, A., Belvedere, C., Nardini, F., Sancisi, N., Conconi, M., Parenti-Castelli, V., 2017. Kinematic models of lower limb joints for musculo-skeletal modeling and optimization in gait analysis. Journal of Biomechanics, doi:10.1016/j.jbiomech.2017.04.029.

Li, J.-D., Lu, T.-W., Lin, C.-C., Kuo, M.-Y., Hsu, H.-C., Shen, W.-C., 2017. Soft tissue artefacts of skin markers on the lower limb during cycling: effects of joint angles and pedal resistance. Journal of Biomechanics, doi:10.1016/j.jbiomech.2017.03.018.

Lofterød, B., Terjesen, T., Skaaret, I., Huse, A.-B., Jahnsen, R., 2007. Preoperative gait analysis has a substantial effect on orthopedic decision making in children with cerebral palsy: comparison between clinical evaluation and gait analysis in 60 patients. Acta Orthopaedica 78, 74-80.

Lu, T.W., O'Connor, J.J., 1999. Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints. Journal of Biomechanics 32, 129-134.

Maslen, B.A., Ackland, T,R., 1994. Radiographic study of skin displacement errors in the foot and ankle during standing. Clinical Biomechanics 9: 291-6.

McLean, S.G., Neal, R.J., Myers, P.T., Walters, M.R., 1999. Knee joint kinematics during the sidestep cutting maneuver: potential for injury in women. Medicine & Science in Sports & Exercise 31, 959–968.

Masum, M.A., Pickering, M.R., Lambert, A.J., Scarvell, J.M., Smith, P.N., 2017. Multi-slice ultrasound image calibration of an intelligent skin-marker for soft tissue artefact compensation. Journal of Biomechanics, doi:10.1016/j.jbiomech.2016.12.030.

Naaim, A., Moissenet, F., Duprey, S., Begon, M., Chèze, L., 2017. Effect of various upper limb multibody models on soft tissue artefact correction: a case study. Journal of Biomechanics, doi:10.1016/j.jbiomech.2017.01.031.

Paul, J.P., 1966. The biomechanics of the hip-joint and its clinical relevance. Proceedings of the Royal Society of Medicine 59, 943-948.

Paul, J.P., 1967. Forces at the human hip joint. PhD thesis (http://theses.gla.ac.uk/3913/)

Paul, J.P., 1969. Loading on the head of the femur. Journal of Anatomy 105, 187–188.

Potvin, B.M., Shourijeh, M.S., Smale, K.B., Benoit, D.L., 2017. A practical solution to reduce soft tissue artifact error at the knee using adaptive kinematic constraints. Journal of Biomechanics, doi:10.1016/j.jbiomech.2017.02.006.

Reinschmidt, C., van den Bogert, A.J., Lundberg, A., Nigg, B.M., Murphy, N., Stacoff, A., Stano, A., 1997a. Tibiofemoral and tibiocalcaneal motion during walking: external vs. skeletal markers. Gait & Posture 6, 98-109.

Reinschmidt, C., van den Bogert, A.J., Nigg, B.M., Lundberg, A., Murphy, N., 1997b. Effect of skin movement on the analysis of skeletal knee joint motion during running. Journal of Biomechanics 30, 729-732.

Richard, V., Cappozzo, A., Dumas, R., 2017. Comparative assessment of knee joint models used in multi-body kinematics optimisation for soft tissue artefact compensation. Journal of Biomechanics, doi:10.1016/j.jbiomech.2017.01.030.

Sangeux, M., Barré, A., Aminian, K., 2017. Evaluation of knee functional calibration with and without the effect of soft tissue artefact. Journal of Biomechanics, doi:10.1016/j.jbiomech.2016.10.049.

Sati, M., de Guise, J.A., Larouche, S., Drouin, G., 1996. Quantitative assessment of skin-bone movement at the knee. The Knee 3, 121-138.

Shimokochi, Y., Shultz, S.J., 2008. Mechanisms of Noncontact Anterior Cruciate Ligament Injury. Journal of Athletic Training 43, 396-408.

Smale, K.B., Potvin, B.M., Shourijeh, M.S., Benoit, D.L., 2017. Knee joint kinematics and kinetics during the hop and cut after soft tissue artifact suppression: time to reconsider ACL injury mechanisms? Journal of Biomechanics, In press.

Solav, D., Camomilla, V., Cereatti, A., Barré, A., Aminian, K., Wolf, A., 2017. Bone orientation and position estimation error using Cosserat point elements and least squares methods: Application to gait. Journal of Biomechanics, doi:10.1016/j.jbiomech.2017.01.026.

Spoor, C.W., Veldpaus, F.E., 1980. Rigid body motion calculated from spatial co-ordinates of markers. Journal of Biomechanics 13, 391-393.

Tranberg, R., Karlsson, D., 1998. The relative skin movement of the foot: a 2-D roentgen photogrammetry study. Clinical Biomechanics 13, 71-76.

Wren, T.A.L., Gorton Iii, G.E., Õunpuu, S., Tucker, C.A., 2011. Efficacy of clinical gait analysis: A systematic review. Gait & Posture 34, 149-153.

Wren, T.A.L., Otsuka, N.Y., Bowen, R.E., Scaduto, A.A., Chan, L.S., Dennis, S.W., Rethlefsen, S.A., Healy, B.S., Hara, R., Sheng, M., Kay, R.M., 2013. Outcomes of lower extremity orthopedic surgery in ambulatory children with cerebral palsy with and without gait analysis: Results of a randomized controlled trial. Gait & Posture 38, 236-241.