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Studies of human locomotion: past, present and future

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Abstract

The study of human locomotion and its applications are examined from a historical viewpoint. Several critical steps in the advancement of the discipline are considered in the context of addressing a particular need to answer fundamental questions regarding the process of human locomotion. In addition, changes in the methods of observation are discussed in terms of the advancement of the field. As an example, the application of a newly developed point cluster technique to reduce the artifact due to skin movement is described. The method was applied to a study of patients with anterior cruciate ligament (ACL) deficient knees. The results demonstrate that patients with ACL-deficient knees have significantly greater than normal anterior–posterior displacement of the femur relative to the tibia during walking. Many of the advancements in the tools for observation and interpretation have been driven by new demands on our fundamental knowledge. Future advancements in the study of human locomotion will likely be motivated by new treatment modalities that require an in depth understanding of the subtle complexities of human locomotion. Future directions are discussed in the context of new methods for reducing errors associated with skin movement combined with information obtained from other imaging methods, such as magnetic resonance imaging. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

As the study of human locomotion and its applications advance, it is useful to examine key historical developments and the influence of these developments on the growth of the field. An analysis of these events helps to predict the direction the field will evolve. Advancement in this field has typically been driven by a need to answer fundamental questions coupled with the technology capable of addressing the questions.

The reasons for studying human locomotion have changed over the centuries. The cave drawings in the Paleolithic Era depicting men and animals in motion were likely partially motivated by survival questions, based on the ability to efficiently move from place to place, escape from predators, and hunt for food. Even the Greek philosophers (500–300 BC) analyzed and described human movement (Lorini et al., 1992). Their observation of human movement was driven by a need to place harmony to the universe. Interestingly, the Greek philosophers believed that the senses deceive and therefore no experimental method can lead to truth; truth could only be reached by logical thought.

The philosophy of the Greeks provides some relevant questions for modern-day studies of human locomotion. Do our senses deceive us and limit our ability to observe and analyze human movement? Do the methods or protocols for measuring human locomotion contaminate the natural characteristics? These are valid concerns and should be kept in mind when interpreting measurements from locomotion studies, especially when attempting to generalize from a specific observation. Some early examples of the limitations of our senses are seen in the depiction of horses in motion (Fig. 1), where the position of the legs were incorrectly drawn (Dagg, 1977). Clearly, the eye was not capable of capturing the sequence of rapid limb movements of horses in motion (Muybridge, 1979). The expanded need for improved knowledge of locomotion drove the introduction of new methods of observation.

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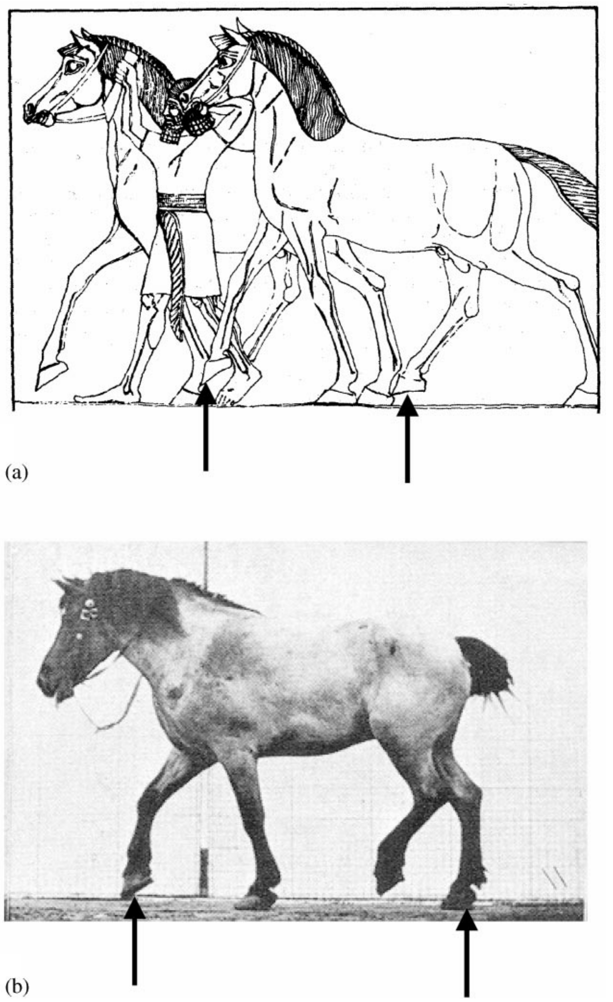

Fig. 1. An artist depiction of the gait of a horse (7 BC) indicates an incorrect pattern of limb movement (Dagg, 1977). The ipsilateral limbs of the horse in the drawing are simultaneously in swing or weight during phases. The eye of the artist could not sample at high enough rates to visually observe the correct pattern of limb movements. As illustrated in (B) from the photographic techniques developed by Muybridge, the contralateral limbs of the horse are simultaneously in swing or weight during phases.

As noted, many of the advancements are motivated by new demands on our fundamental knowledge. The ability to observe and interpret measurements of human movement have been the primary factors limiting growth of the field. The purpose of this paper is to examine the direction of future developments in the study of human locomotion. The factors that influenced several major developments in the study of human locomotion over the last several centuries will be considered. In addition, future advancements in the study of human locomotion will be discussed in the context of new technology and ways that this new technology can be applied to the evaluation of musculoskeletal disease and injury.

2. Methods applied to the study of human locomotion

The advancement of the study of locomotion remains dependent on the development of new tools for observation. Over the last several centuries, there have been several fundamental advancements that have made a substantial impact on our understanding of the process of human locomotion.

The Weber brothers (1836) reported one of the first quantitative studies of the temporal and distance parameters during human locomotion. Their work established a model for subsequent quantitative studies of human locomotion. The works of two contemporaries, Marey (1977) and Muybridge (1979), were among the first to quantify patterns of human movement using photographic techniques. Muybridge used a series of cameras to take multiple pictures in rapid succession of both animals and humans in movement. Also during that time period, Wilhelm Braune (an anatomist) and Otto Fisher (a mathematician) reported measurements of body segment movements to calculate joint forces and energy expenditures using Newtonian mechanics (Braune and Fischer, 1988). Interestingly, their work was motivated by military applications related to improving the efficiency of troop movement.

During the 1950s there was a need for an improved understanding of locomotion for the treatment of World War II veterans. The classic work at the University of California (Eberhart, 1947; Inman et al., 1981) provided a tremendous resource of knowledge related to the mechanics of human movement. The work at the University of California formed the basis for many of the fundamental techniques currently used for the study of human locomotion. More recently, instrumentation and computer technologies have provided new opportunities for the advancement of the study of human locomotion. The limitations with respect to automated motion capture as well as measurement reduction no longer exist. This new methodology has made it feasible to extend the application of kinetic analysis to clinical problems.

Currently, one of the primary technical factors limiting the advancement of the study of human movement is the measurement of skeletal movement from markers placed on the skin. The most frequently used method for measuring human movement involves placing markers or fixtures on the skin's surface of the segment being analyzed (Benedetti and Cappozzo, 1994). The movement of the markers is typically used to infer the underlying relative movement between two adjacent segments (e.g. knee joint) with the goal of precisely defining the movement of the joint. Skin movement relative to the underlying bone is a primary factor limiting the resolution of detailed joint movement using skin-based systems (Cappozzo et al., 1997; Sati et al., 1996; Reinschmidt et al., 1997; Holden et al., 1997).

Skeletal movement can be measured using alternative approaches to a skin-based marker system. These approaches include stereoradiography (Jonsson and Karrholm, 1994), bone pins (LaFortune et al., 1992) external fixation devices (Holden et al., 1997) or single plane fluoroscopic techniques (Banks and Hodge, 1996; Stiehl et al., 1995). While these methods provide direct measurement of skeletal movement, they are invasive or expose the test subject to radiation. In addition, these methods also impede natural patterns of movements and care must be taken when attempting to extrapolate these types of measurements to natural patterns of locomotion.

With skin-based marker systems, in most cases, only large motions such as flexion–extension have acceptable error limits. Cappozzo et al. (1996) have examined five subjects with external fixator devices and compared the estimates of bone location and orientation between coordinate systems embedded in the bone and coordinate systems determined from skin-based marker systems for walking, cycling and flexion–extension activities. Comparisons of bone orientation from true bone embedded markers versus clusters of three skin-based markers indicate a worst-case root mean square artifact of 7°.

The vast majority of current analysis techniques model the limb segment as a rigid body, then apply various estimation algorithms to obtain an optimal estimate of the rigid body motion. One such rigid body model formulation is given by Spoor and Veldpas (1988); they have described a rigid body model technique using a minimum mean square error approach that lessens the effect of deformation between any two time steps. This assumption limits the scope of application for this method, since markers placed directly on skin will experience non-rigid body movement. Lu and O'Connor expanded the rigid body model approach; rather than seeking the optimal rigid body transformation on each segment individually, multiple, constrained rigid body transforms are sought, modeling the hip, knee, and ankle as ball and socket joints (Lu and O'Connor, 1999). The difficulty with this approach is the model of the joints as a ball and socket; all joint translations are treated as artifact, clearly a limitation for knee motion. Lucchetti et al. (1998) take an entirely different approach, using artifact assessment movements to determine the correlation between flexion–extension angles and apparent skin marker artifact trajectories. A limitation of this approach is the assumption that the skin motion during the artifact assessment movements is the same as during the dynamic activities.

A recently described (Andriacchi et al., 1994, 1998) point cluster technique (PCT) employs an overabundance of markers (a cluster) placed on each segment to minimize the effects of skin motion artifact (Fig. 2). The basic PCT can be extended to minimize skin motion artifact by optimal weighting of the markers according to their degree of deformation. Another extension of the basic PCT (Alexander and Andriacchi, 2000) corrects for error induced by segment deformation associated with

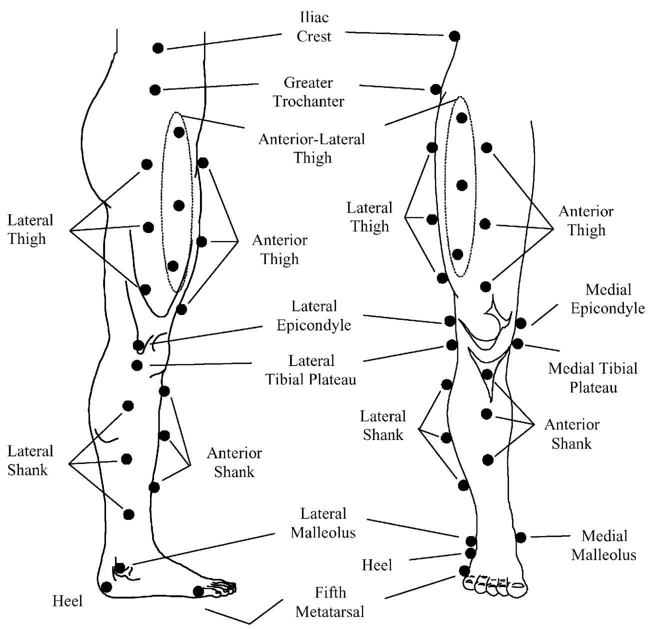

Fig. 2. An illustration of the marker configuration used for the point cluster technique.

skin marker movement relative to the underlying bone. This is accomplished by extending the transformation equations to the general deformation case, modeling the deformation by an activity-dependent function, and smoothing the deformation over a specified interval to the functional form. A limitation of the approach is its computational complexity.

As instruments have been developed to enhance our ability to observe human movement, models have been used to develop information that cannot be directly observed. Typically, models are an abstraction in the form of a physical construction governed by principles of physics and mathematics. Models of biomechanical systems provide the basis for the seeking of truth through application of physical laws. Borelli (1608–1679)(1989) was among the first to apply physical laws to the analysis of the locomotion of animals. Borelli, in his classic work *De Motu Animalum* (1680), recognized that complex biological structures could be reduced to simplified constructs that facilitated the estimation of forces and patterns of movement. Borelli's work has been fundamental to the development of biomechanical models and the study of human movement.

In modern times, models have played an important role in generating information that cannot be directly observed. In particular, the prediction of intersegmental forces and moments has been extremely valuable in improving our understanding of the musculoskeletal system. Intersegmental forces and moments are approximated by modeling the body as a system or rigid links and measuring the three-dimensional position of the limb segments and external ground reaction force (Bresler and

Frankel, 1953). The frequency characteristics and filtering considerations for these types of motion measurements are described by Winter (Winter et al., 1974). In general, these calculations have formed the basis for the prediction of muscle forces and joint contact forces. The information from these studies has been applied to a number of fundamental and clinical studies. In general, the same methodology has been used for both the hip and knee joints. The early work from the group at Strathclyde (Paul, 1971; Morrison, 1970) used a reduction method to solve the statically indeterminate problem related to the redundant set of internal forces that can balance external intersegmental moments.

3. Results of applying the study of locomotion to clinical problems

The application of quantitative studies of human locomotion has contributed substantially to the improvement in the treatment of injury and disease of the musculoskeletal system. In particular, the treatment of neuromuscular disorders has been improved by analyzing dynamic gait characteristics of patients prior to treatment. Perry (1992) and Sutherland (1964) have been pioneers in the clinical application of gait analysis techniques to assist in the treatment of patients with cerebral palsy. The work of Perry and Sutherland has provided a basis for improving the outcome of surgical and nonsurgical treatment of cerebral palsy. Computerized models (Delp et al., 1990) of the musculoskeletal system have also contributed substantially to understanding the biomechanical effects of surgical treatment for cerebral palsy. As these models become more fully integrated with gait analysis, there will be new opportunities to improve the outcome of treatment.

The application of gait analysis to the treatment of patients with cerebral palsy has primarily involved the application of kinematic and EMG measurements. There have also been clinical applications of kinetic measurements of human locomotion. In particular, kinetic measurements, combined with musculoskeletal models, have been used to predict changes in joint contact forces and muscle firing patterns and joint contact loads. It has been shown (Prodromos et al., 1985; Schipplein and Andriacchi, 1991; Berchuck et al., 1990) that patients develop adaptive changes in gait patterns that can be analyzed in terms of the changes in kinetic measures. The identification of function adaptation to musculoskeletal disorders is an important consideration in the clinical application of the study of human locomotion. The ability to identify these types of adaptations is dependent on the methods used to acquire motion measurements. Care must be taken when introducing any artificial stimulus while measuring human movement. Insertion of bone pins, the strapping of tight fixtures around limb segments or constraints to normal movement patterns (such as required for fluoroscopic or other radiographic imaging measurements) can introduce artifacts into the observation of human movement. In some cases, these artifacts can lead to incorrect interpretations. The quest to obtain skeletal movement during human motion capture can introduce artifacts into the normal pattern of human movement. For example, even walking on a treadmill can produce changes in the stride length–walking speed relationships (Banks et al., 1999). As the Greek philosophers suggested, our senses can be fooled. The potential for measurement-induced artifact is particularly relevant to studies where subtle gait changes associated with a reprogramming of locomotor patterns might be present.

Ideally, the measurement system/protocol should only minimally encumber the subject. It is useful to examine a specific example of an adaptive change in patterns of locomotion observed in patients with anterior cruciate deficient knees. Several studies have determined that patients with anterior cruciate ligament (ACL) deficiency adapt to their injury over time. Typically patients dynamically compensate for instability in the sagittal plane by altering the balance between quadriceps and hamstring activity (Fig. 3). The modifications in function (Andriacchi et al., 1997; Branch et al., 1989; Tibone et al., 1986), are presumably adaptations produced by a subconscious protective mechanism to avoid the excessive anterior displacement of the tibia that can occur in the absence of the ACL (Andriacchi, 1990). However, it is not likely that these adaptations are the result of a single stimulus that occurs during each cycle of the activity. It is more likely that these adaptations are the result of repetitive experiences following the loss of the ACL. It is possible that reprogramming of the locomotor process occurs such that the adaptations occur before instability and excessive anterior displacement results. This can be accomplished by altering the pattern of muscle contraction as part of an adaptive locomotor program. The adaptations anticipate the instability and, thus, avoid the abnormal displacement. General locomotor reprogramming could be part of a learning process that takes place during the early stages following an ACL injury. It would be necessary that the locomotor system be reprogrammed in a manner that would anticipate instability prior to the occurrence of the episode that would produce instability, since the latency time for muscle contraction would be too slow to instantaneously respond to a rapid stimulus.

Does reprogramming of the locomotor system protect the ACL-deficient knee? While only long-term clinical studies can directly answer this question, the proper application of motion studies can provide some important answers. Do the dynamic adaptations during gait reduce the increased anterior displacement (measured passively) of the tibia following ACL?

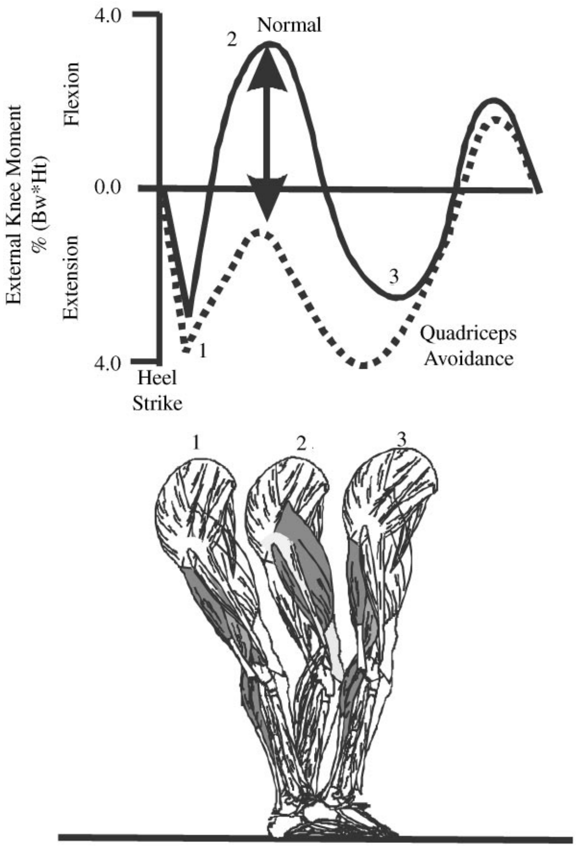

Fig. 3. The flexion–extension moment pattern at the knee demonstrates an adaptation in patients with ACL-deficient knees to reduce the net quadriceps moment during the stance phase of walking. The axis label refers to the external flexion–extension moment. This moment is balanced by the net moment generated by the action of the flexor and extensor muscles at the knee. For example, a net moment dominated by the quadriceps muscles would be needed to balance an external flexion moment.

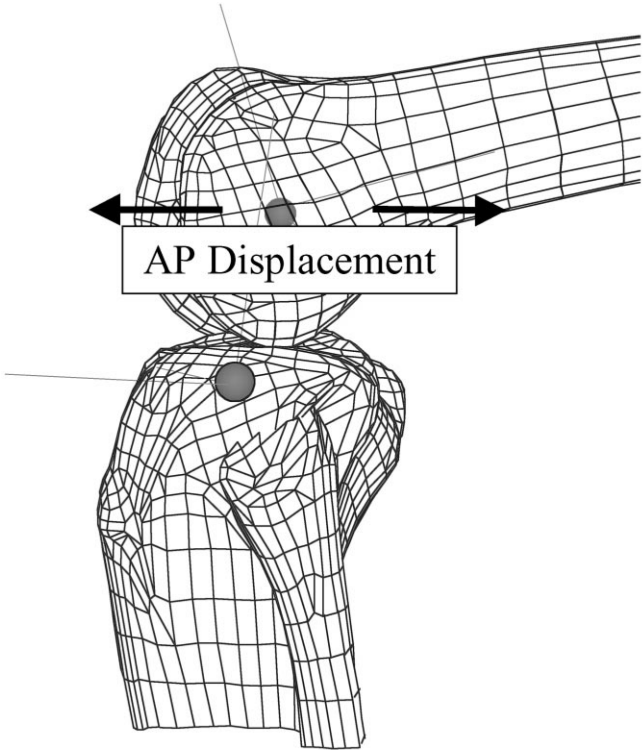

Fig. 4. The femoral reference point located at the middle point of the trans-epicondylar axis of the femur was used to quantify AP movement of the femur with respect to the tibia.

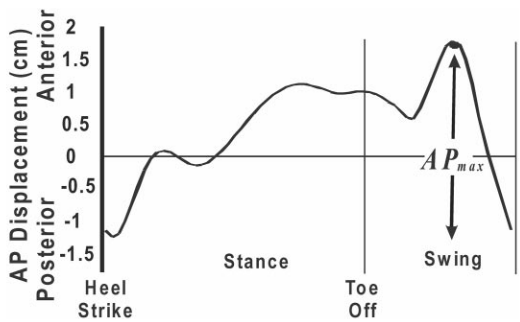

Fig. 5. The characteristics of the AP movement of the femur with respect to the tibia during the gait cycle. The over all range, AP_{max}, was used to quantify the characteristics of dynamic stability, and differences observed between normal subjects and patients with anterior cruciate ligament deficiency.

The point cluster technique (Andriacchi et al., 1998) was used to study the anterior–posterior (AP) motion of the knee during walking. The AP movement of a point located on the trans-epicondylar axis of the femur was determined relative to an axis fixed in the tibia (Fig. 4). The characteristics of the AP movement had several characteristics common to all subjects (Fig. 5). At heel strike with the knee at full extension, the tibia is at its maximum anterior position during the gait cycle. The next key event occurs at terminal extension where the tibia is located posteriorly again while the knee is near full extension. Thus, heel strike and terminal extension provide two events where the tibia is located over a range of AP positions relative to the femur. Clearly, the dynamic forces during gait determine these positions since passive motion of the knee would show a one-to-one relationship between knee flexion angle and AP position of the knee (Draganich et al., 1987). During the swing phase with the limb unloaded, the tibia moves to its maximum posterior position at maximum knee flexion, and then moves forward rapidly as the knee extends prior to heel strike. The curve represented in Fig. 5 was used to assess the dynamic AP motion of the knee in patient with ACL-deficient knees (Hasan et al., 1998) that did not develop the neuromuscular adaptation previously described. The maximum AP displacement for patient with ACL-deficient knees (2.2 ± 0.5 cm) was significantly greater ($p < 0.002$) than normal (1.3 ± 0.4 cm). Although preliminary in nature, these results suggest that in the absence of neuromuscular adaptations, the AP displacement of the ACL-deficient knee is greater than that during normal walking.

A final example of the potential clinical importance of functional adaptation has been reported (Prodromos et al., 1985; Wang et al., 1990; Schnitzer et al., 1993) in patients with osteoarthritis (OA) at the knee. The adduction moment at the knee during gait has been shown to influence the outcome of high tibial osteotomy (HTO) for varus gonarthrosis. Patients with a low preoperative adduction moment had a lower adduction moment following HTO, and better functional and radiographic outcome. These results could not be predicted from pre- or post-operative static alignment (mechanical axis) measurements. Clearly, individual variations in dynamic loading during gait strongly influenced the clinical outcome of a treatment for medial compartment OA. Do these individual variations also influence the natural rate of disease progression?

The appropriate deployment and selection of newer treatment interventions for OA is dependent on the development of better methods for the assessment of the disease process. Degenerative changes to articular cartilage can be described in biological, mechanical and morphological terms. From a morphological viewpoint, there has been substantial progress in our ability to study cartilage using MRI. From a mechanical viewpoint, recent studies have demonstrated a relationship between the dynamic loads at the knee during gait and progression of knee OA. The combination of imaging methods with functional kinematic information obtained during walking could greatly enhance our ability to study OA.

Techniques have been developed which allow dynamic visualizations of the high-resolution 3D internal images derived from the MR scans. The motion of the subject-specific anatomic elements can be driven by data acquired from the motion lab. This is achieved by cross-registering the fiducial markers in both the MRI and the motion lab (Fig. 6). The skin-mounted markers are filled with gadalinium and covered with a retro-reflective material, rendering them opaque to both imaging modes. Optimization techniques are then used to calculate the transformations needed in the visualizations, bringing the geometric representation of the anatomic element from the MR coordinate system to the motion lab coordinate system.

To address these issues, further developments are needed involving the integration of morphological and material property data with kinematic and kinetic data obtained in a laboratory. New developments in medical imaging have made it possible to obtain three-dimensional segmented images of bone, cartilage and connective tissue surrounding joints. The next major developments in this field will likely incorporate information from medical imaging into a construct suitable for functional testing.

4. Conclusions

The study of human locomotion has contributed to the advancement of fundamental knowledge as well as

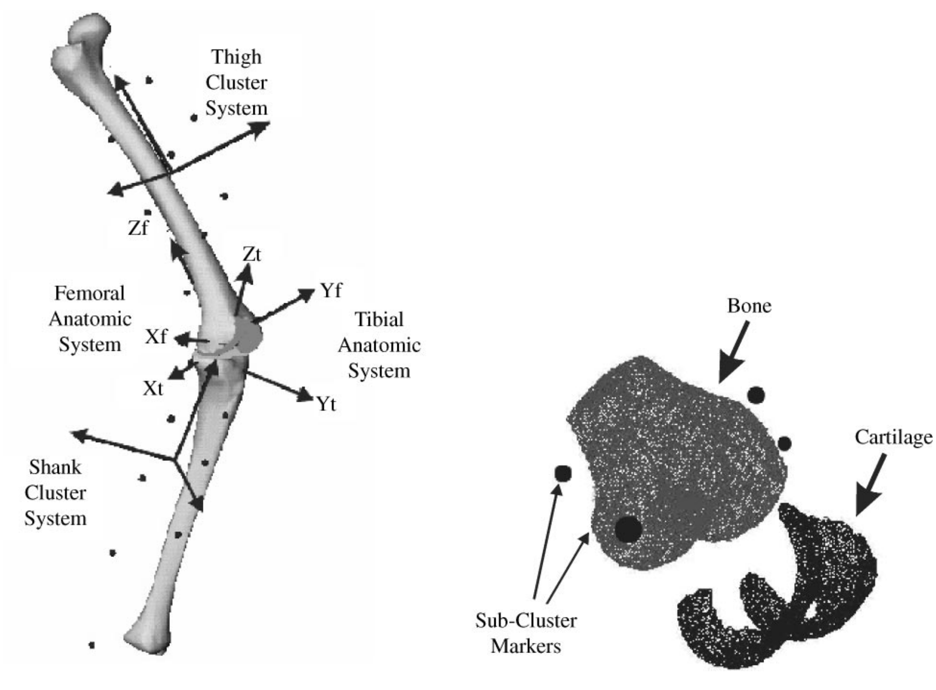

Fig. 6. An illustration of the three-dimensional reconstruction of the cartilage and proximal femur derived from a magnetic resonance imaging. The reconstruction is registered with a coordinate system derived from the point cluster technique. The combination of the two techniques provides an analysis of the load-bearing areas of the articular cartilage during activities such as walking.

applied fields ranging from military applications to health care. Clearly, there are unanswered questions regarding the factors controlling various patterns of locomotion adopted by individuals following injury or disease. There is substantial evidence that some individuals adapt their gait to compensate for instability, pain or neuromuscular pathology. A critical challenge for the future is to develop new and more powerful modeling and observation techniques. This will lead to improvements in our fundamental understanding of these locomotion processes, which in turn will advance our abilities to improve clinical outcomes.

References

Alexander, E.J., Andriacchi, T.P., 2000. Correcting for deformation in skin based marker systems. Journal of Biomechanics, in review.

Andriacchi, T.P., 1990. Dynamics of pathological motion: applied to the anterior cruciate deficient knee. Journal of Biomechanics 23 (Suppl. 1), 99–105.

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

Andriacchi, T.P., Hurwitz, D., Bush-Joseph, C., Bach, B., 1997. Clinical implications of functional adaptations in patients with ACL deficient knees. Sportorthopadie-Sporttraumatologie 13 (3), 153–160.

Andriacchi, T.P., Sen, K., Toney, M.K., Yoder, D., 1994. New developments in musculoskeletal testing. Proceedings of the Canadian Society of Biomechanics, pp. 221–222.

Banks, S.A., Hodge, W.A., 1996. Accurate measurement of three-dimensional knee replacement kinematics using single-plane fluoroscopy. IEEE Transactions on Biomedical Engineering 43 (6), 638–649.

Banks, S.A., Otis, J., Backus, S., Laskin, R., Campbell, D., Lenhoff, M., Furman, G., Haas, S., 1999. Integrated analysis of knee arthroplasty mechanics using simultaneous fluoroscopy, force plates, and motion analysis. 45th Annual Meeting of the Orthopedic Research Society, 0147.

Benedetti, M.G., Cappozzo, A., 1994. Anatomical landmark definition and identification in computer aided movement analysis in a rehabilitation context II (Internal Report). Universita Degli Studi La Sapienza, pp. 1–31.

Berchuck, M., Andriacchi, T.P., Bach, B.R., Reider, B.R., 1990. Gait adaptations by patients who have a deficient ACL. Journal of Bone and Joint Surgery 72A, 871.

Borelli, A.G., 1989. On the movement of animals. Rome 1680 (1st part) and 1681 (2nd). In: Cappozzo, A., Marchetti, M., Tosi, V. (Eds.), Biolocomotion: A Century of Research Using Moving Pictures. Promograph, Rome, p. 125.

Branch, T.P., Hunter, R., Donath, M., 1989. Dynamic EMG analysis of anterior cruciate deficient legs with and without bracing during cutting. American Journal of Sports Medicine 17, 35.

Braune, W., Fischer, O., 1988. Determination of the moments of inertia of the human body and its limbs. In: Cappozzo, A., Marchetti, M., Tosi, V. (Eds.), Biolocomotion: A Century of Research Using Moving Pictures. Promograph, Rome, pp. 125.

Bresler, B., Frankel, J.P., 1983. The forces and moments in the leg during level walking. Transactions of the American Society of Mechanical Engineering 48A, 62.

Cappozzo, A., Capello, A., Della Croce, U., Pensalfini, F., 1997. Surface marker cluster design criteria for 3-D bone movement reconstruction. IEEE Transactions on Biomedical Engineering, 44.

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

Dagg, A.I., 1977. Running, walking and jumping. In: Cappozzo, A., Marchetti, M., Tosi, V. (Eds.), Biolocomotion: A Century of Research Using Moving Pictures. Promograph, Rome, pp. 19.

Delp, S.L., Loan, J.P., Hoy, M.G., Zajac, F.E., Topp, E.L., Rosen, J.M., 1990. An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures. IEEE Transactions on Biomedical Engineering 37, 757–767.

Draganich, L.F., Andriacchi, T.P., Andersson, G.B.J., 1987. Interaction between intrinsic knee mechanics and the knee extensor mechanism. Journal of Orthopaedic Research 5, 539–547.

Eberhart, H.D., 1947. Fundamental studies of human locomotion and other information relating to design of artificial limbs. Subcontractors' Report to National Council, Berkeley, California.

Hasan, S.S., Hurwitz, D.E., Bush-Joseph, C.J., Bach Jr. B.R., Andriacchi, T.P., 1998. Dynamic evaluation of knee instability during gait in anterior cruciate deficient patients. 44th Annual Meeting Orthopaedic Research Society, p. 805.

Holden, J.P., Orsini, J.A., Siegel, K.L., Kepple, T.M., Gerber, L.H., Stanhope, S.J., 1997. Surface movements errors in shank kinematics and knee kinetics during gait. Gait and Posture 3, 217–227.

Inman, V.T., Ralston, H.J., Todd, F., 1981. In: Lieberman, J.C. (Ed.), Human Walking. Williams & Wilkins, Baltimore, London.

Jonsson, H., Karrholm, J., 1994. Three-dimensional knee joint movements during a step-up: evaluation after cruciate ligament rupture. Journal of Orthopedic Research 12 (6), 769–779.

LaFortune, M.A., Cavanagh, P.R., Sommer, H.J., Kalenak, A., 1992. Three dimensional kinematics of the human knee during walking. Journal of Biomechanics 25, 347–357.

Lorini, G., Bossi, D., Specchia, N., 1992. The concept of movement prior to Giovanni Alfonso Borelli, 23.

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

Lucchetti, L., Cappozzo, A., Capello, A., Della Croce, U., 1998. Skin movement artefact assessment and compensation in the estimation of knee-joint kinematics. Journal of Biomechanics 31, 977–984.

Marey, E.-J., 1977–1978. La photographie du mouvement, Catalogue de l'exposition du Musee National d'Art Moderne Centre Georges Pompidou. In: Cappozzo, A., Marchetti, M., Tosi, V. (Eds.), Biolocomotion: A Century of Research Using Moving Pictures. Promograph, Rome, p. 88.

Morrison, J.B., 1970. The mechanics of the knee joint in relation to normal walking. Journal of Biomechanics 3, 51–61.

Muybridge, 1979. Complete human and animal locomotion (All 781 Plates from the 1887 Animal Locomotion). In: Cappozzo, A., Marchetti, M., Tosi, V. (Eds.), Biolocomotion: A Century of Research Using Moving Pictures. Promograph, Rome, p. 69.

Paul, J.P., 1971. Comparison of EMG signals from leg muscles with the corresponding force actions calculated form walk path measurements. Human Locomotor Engineering, 6–26.

Prodromos, C.C., Andriacchi, T.P., Galante, J.O., 1985. A relationship between knee joint loads and clinical changes following high tibial osteotomy. Journal of Bone and Joint Surgery 67A (8), 1188–1194.

Perry, J., 1992. In: Willoughby, C.D. (Ed.), Gait Analysis — Normal and Pathological Function. Slack, New Jersey.

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

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

Schipplein, O.D., Andriacchi, T.P., 1991. Interaction between active and passive knee stabilizers during level walking. Journal of Orthopedic Research 9, 113–119.

Schnitzer, T.J., Popovich, J.M., Andersson, G.B., Andriacchi, T.P., 1993. Effect of piroxicam on gait in patients with osteoarthritis of the knee. Arthritis Rheumatism 36 (9), 1207–1213.

Spoor, C.W., Veldpas, F.E., 1988. Rigid body motion calculated from spatial coordinates of markers. Journal of Biomechanics 13, 391–393.

Stiehl, J.B., Komistek, R.D., Dennis, D.A., Paxson, R.D., Hoff, W.A., 1995. Fluoroscopic analysis of kinematics after posterior-cruciate-retaining knee arthroplasty. Journal of Bone and Joint Surgery 77, 884–889.

Sutherland, D.H., 1964. Gait disorders in childhood and adolescence. Williams & Wilkin, Baltimore.

Tibone, J.E., Antich, T.J., Fanton, G.S., Moynes, D.R., Perry, J., 1986. Functional analysis of anterior cruciate ligament instability. American Journal of Sports Medicine 14, 276.

Wang, J.-W., Kuo, K.N., Andriacchi, T.P., Galante, J.O., 1990. The influence of walking mechanics and time on the results of proximal tibial osteotomy. Journal of Bone and Joint Surgery 72A (6), 905–913.

Weber, W., Weber, E., 1836. Mechanik der menschlichen Gehwerkzeuge. In: Cappozzo, A., Marchetti, M., Tosi, V. (Eds.), Biolocomotion: A Century of Research Using Moving Pictures. Promograph, Rome, p. 126.

Winter, D.A., Sidwall, H.G., Hobson, D.A., 1974. Measurement and reduction of noise in kinematics of locomotion. Journal of Biomechanics 7, 157–159.