

## A5–EXPERIMENTAL METHODS IN BIOMECHANICS

Organised by A.M. Wilson, N. Rowe and T. Speck for the Biomechanics Group

### A5.1–What in vitro measures can predict in vivo muscle performance?

R.C. Woledge, University College, London

The minimum set of measurements required for mechanical predictions are

- A. the force–length relation
- B. the force–velocity curve
- C. the stress–strain relation of the series elasticity
- D. the time course of activation and relaxation

Also desirable but less essential are

- A. the temperature dependence of A and D
- B. the characteristics of shortening de-activation.

If you want to make energetic cost predictions you would also need

- A. the velocity dependence of the rate of ATP splitting

- A. isometric contraction at a range of lengths
- B. steady force during shortening at steady velocity. The ‘step & ramp’ protocol is superior to a simple isovelocity protocol. The measurement of the velocity of unloaded shortening by the ‘slack-step’ protocol is an excellent addition. In these experiments it is important to be aware of the effects of parallel elasticity.
- C. can also be obtained from the ‘step & ramp’ protocol.
- D. can be inferred from the time course of isometric contraction using a simple model of the activation processes.
- E. where it is not possible to make the in vitro observations at the in vivo temperature extrapolation might be used.
- F. The ‘step & ramp’ protocol gives some information

An example of the successful use of B, C and D to predict the behaviour of muscle in contraction resembling the in vivo tasks is in Curtin et al (JEB, **201**, 103). Other examples will be presented at this meeting.

### A5.2–Measuring the dynamics of muscle function in vivo: comparisons of design and function across locomotor modes

A.A. Biewener, CFS, Harvard University

Limb muscles generate force and change length under dynamic conditions of locomotor movement. In vivo

measurements of muscle activation, force development, and length change are therefore critical to understanding how muscle performance is modulated in relation to work and force. New methods and approaches allow direct measurements of muscle fascicle length change (via sonomicrometry) and force development (via tendon buckles or bone strain gauges) to be related to recordings of muscle activation (via electromyography). Different patterns of force–length contractile behavior and muscle–tendon architecture can be expected across differing locomotor modes. Whereas terrestrial gaits benefit from isometric or stretch–shorten patterns of force development and elastic energy recoil from short pennate-fibred muscles and long tendons, swimming and jumping favor substantial muscle shortening strain to generate work. By timing the onset of muscle activation during muscle stretch or isometric contraction, the rate and magnitude of force developed is enhanced. This favors greater work and power, in addition to more economical force generation. Alternatively, longer fibered muscles with short or absent tendons may provide greater control of limb movements. The extent to which muscle–tendon architecture constrains the modulation of contractile function is important for understanding how different muscles within a limb may be recruited to mediate changes in locomotor performance.

Biewener (1998) *Am. Zool.* 38: 703–717.

Biewener and Gillis (1999) *J. exp. Biol.* 202: 3387–3396.

Biewener and Roberts et al. (2000) *Exer. & Sport Sci. Rev.* 28: 99–107.

### A5.3–Ultrasound and MRI for studying muscle–tendon function in vivo

C.N. Maganaris, Manchester Metropolitan University

This review presents data on in vivo human muscle and tendon properties obtained recently using ultrasound and MRI. The force–length relations of the human tibialis anterior (TA) and gastrocnemius (GS) muscles and tendons were examined.

The force–length relations of the two muscles were obtained by combining dynamometry-based measurements of maximal isometric ankle joint moment, ultrasound-based measurements of pennation angle and fascicle length, MRI-based measurements of tendon moment arm length and modelling-based calculations of force, over the entire range of ankle movement. The results show that although the plateau region of force–length relation is reached by the TA muscle, the GS muscle operates in the ascending limb only, thus suggesting that the muscle length dictating sarcomere num-

ber may not be the length corresponding to maximal force (1, 3).

The force–length relations of the two tendons were obtained by combining dynamometry-based measurements of isometric ankle joint moment, MRI-based measurements of tendon moment arm length and ultrasound-based measurements of tendon elongation. The results show that although the two tendons have different physiological functions and are subjected to different loads, they have very similar *in vivo* material properties: their Young's modulus is  $\sim 1.2$  GPa and their mechanical hysteresis is  $\sim 18\%$  (2). This finding indicates that adjustments in tendon structural properties to physiological loading are accomplished by altering the tendon's dimensions, not its material.

1. Maganaris, C. N. 2001 *Acta Physiol. Scand.* 172, 279–285.
2. Maganaris, C. N. 2002 *J. Biomech.* 35, 1019–1027.
3. Maganaris, C. N. 2003. *Clin. Anat.* In press.

#### **A5.4—Measuring motor unit recruitment patterns in mixed mammalian muscle**

James M. Wakeling, Faculty of Kinesiology, University of Calgary

When mammalian skeletal muscle is activated, action potentials travel along the sarcolemmas of its muscle fibres. During the propagation of these action potentials, voltage sensitive ion channels on the sarcolemma open and close, resulting in ion movements and thus current flow across the membranes. Both the shape and conduction velocity of an action potential depend on the rates of ion movements across the sarcolemma, and thus factors such as muscle fatigue which affect ion movement also affect the spectral properties of the myoelectric signal. Recent studies have also shown that large differences in the frequency spectra can occur between different types of muscle fibre. Electromyography measures the summed myoelectric signals from the muscle fibres surrounding the recording electrodes. Therefore, an electromyographic recording contains information on the physiological status and the fibre-type recruitment pattern of the activated muscle. The application of wavelet techniques to the processing of myoelectric signals results in the spectral properties of the myoelectric signal being resolved through time. During each stride bursts of muscle activity can be observed at distinct myoelectric frequencies and at distinct times, and such observations suggest that different types of muscle fibre are recruited for different tasks. This presentation will discuss how to resolve a myoelectric signal into its properties in time–frequency space, and how to interpret the results in the context of the physiological status and fibre-type recruitment of the muscle.

#### **A5.5—Mechanical strain as an environment, stimulus, objective and danger for bone cells**

L. Lanyon, Veterinary Basic Sciences, The Royal Veterinary College

Bones' have a number of roles in life but in each it is important that they do not fracture. To protect against this requires appropriate internal and external organisation. Bones have an advantage over inanimate structures in that the cells which construct and maintain them can also adapt their architecture in relation to the loads they encounter. A disadvantage of relying on such adaptation is that fracture is usually caused by conditions rarely if ever previously encountered. As if to cope with this situation bone cells adjust their (re)modelling activity most vigorously in response to short periods of high strains, high strain rates and unusual strain distributions. These may be the best approximation available to the strain situations likely to cause fracture. Although it is still not known which specific mechanical events stimulate adaptive bone cell activity once transduction has occurred the strain-related responses within the cells are the same as those produced by other stimuli including biochemical and hormonal influences. Of current interest is the finding that one of these early pathways involves the estrogen receptor. In mice without functional ER $\alpha$  the osteogenic response to loading is threefold less than in wild type littermates. *In vitro* osteoblast-like cells respond to strain by phosphorylation of the ER, activation of estrogen response elements and proliferation. These can all be blocked at the ER. This commonality of processing information from estrogen and mechanical strain may explain the similarity in many responses to these two influences and the etiology of post-menopausal osteoporosis.

#### **A5.6—Towards an Understanding of the *in vivo* Biomechanics of Joints**

W. Herzog, Faculties of Kinesiology, Engineering and Medicine, The University of Calgary

Biomechanics deals with the internal and external forces acting on a system and the effects that these forces have on the system. Understanding the forces, pressures, stresses and strains acting on joints are important for movement analysis and control, for understanding adaptive and degenerative processes in joints, and for injury prediction and prevention. In the ideal case, one would

like to know the instantaneous, in vivo muscle forces, and the stresses and strains in each of the joint tissues during normal movement. However, this is currently not possible as stresses cannot be measured, and strains and muscle forces are hard to obtain. Here, we would like to discuss some experimental and theoretical techniques to obtain in vivo muscle forces, joint contact pressures, and the stresses and strains in soft tissues for physiologic magnitudes of joint loading. These techniques include force measurements using buckle-type and implantable force transducers, pressure measurements in intact diarthrodial joints, non-linear optimization approaches and continuum mechanics modeling of multi-phasic soft tissues. Furthermore, we will present specific approaches on how to obtain the biological responses of soft tissues to controlled ex vivo and in vivo loading conditions. These approaches include the loading of tendinous and cartilaginous tissues in vivo, and measuring the adaptive response using molecular biology approaches and cell death, as well as measuring the gene expressions, calcium transients and other cell signaling mechanism prior to, during, and following loading of isolated soft tissue cells.

#### **A5.7–Biotribology Methods: Measurements of Friction and Adhesion on Biological Objects**

S.N. Gorb, Max-Planck-Institute for Metals Research, Stuttgart

Biological systems have in the course of evolution developed surface mechanisms which fulfill specific mechanical functions such as attachment, friction, body cleaning, air holding, increase of aerodynamic activity, sound generation etc. Such functions require a variety of optimized surface patterns, whose scale is in the micron and submicron range. The main challenge is to investigate the interrelationship between ultrastructure, mechanical material properties, local tribological properties and global attachment–detachment performances in such systems. In this paper, several methods for measuring contact forces in the milli- and micro-Newton range at complex patterned biological surfaces are demonstrated. (1) Local mechanical property measurements include testing of contact deformation and viscoelastic response of surfaces by microindentation. (2) Global attachment forces are measured by the centrifugal force tester and load cell force transducer combined with regular and high-speed videorecordings on living objects. (3) Local attachment performance is characterised by normal and shear testing using micro-force tester Basalt-01 (Tetra, Ilmenau, Germany). Several case studies carried out on particular insect attachment devices are presented

#### **A5.8–Field measurements of swaying and damping in plants: *Arundo donax* as a damped harmonic oscillator**

O. Speck; H.-CH. Spatz; Biology, University of Freiburg

The giant reed (*Arundo donax* L.) consists of tall hollow stems (4–6 m high) and an extensive underground rhizome system with solid branches bearing adventitious roots. Quantitative analyses of video recordings using the software package SIMI Motion prove that *Arundo donax* responds to deflections of the stem with damped harmonic bending oscillations. In addition, a special device was used consisting of two laser pointers, which beams are directed towards two slits on a detector unit. Upon swaying the plant interrupts one or the other of the light beams. The time between the interruption of alternate laser beams provides a measure of the velocity of the plant at the height of the optical recording and thus a measure of the amplitude. Damping of the oscillation is observed as the decrease of the amplitude with time over several cycles. The logarithmic decrement can be used to calculate the relative damping as a measure of the plant's capacity to dissipate vibrational energy. A comparison of the relative damping of plants with and without leaves shows that the highly significant difference is not only due to aerodynamic resistance of the leaves. Structural damping contributes considerably to the overall damping of the foliate *Arundo donax* stem. By stepwise removal of the underground plant organs the influence of rhizome, roots and soil on the vibration behaviour was determined. The data indicate that underground plant organs as well as leaf sheaths covering the nodes have no significant influence on damping.

#### **A5.9–Innovative Techniques in 3D motion Analysis**

J Carter, M.S. Nixon, J. Shutler, M.G. Grant, University of Southampton

Motion Capture and Analysis at Southampton is driven from a very different point of view, that of biometrics and identification rather than exact measurement. In this talk we will initially describe how our application drives our algorithms and indicate how these differ from a more conventional approach.

In a laboratory environment side views with single camera are often used. We will describe a hierarchical algorithm, which uses a pseudo-biomechanical model to limit the search space for a more general feature limb extraction tool. We will show results for both running and walking.

In the case where multiple, known camera views are available it is possible to synthesise a three dimensional representation of complex objects, including human beings. We will describe a system that does this effi-

ciently, and will demonstrate it in a system with three synchronised cameras, showing how we can build surface models, perform effective background segmentation and generate almost arbitrary views. These views are then combined with a simple motion model to track limbs in 3-D.

Finally we will describe a new and novel technique, which exploits perspective geometry, fixed limb lengths and the inherent periodicity of human gait. This allows average limb motion to be reconstructed in an unconstrained and unknown environment, and in time, without any markers or other aids to feature detection.

We conclude with a brief discussion of how these techniques may be combined and extended to provide a complete description of human movement.

#### **A5.10—Reconstructing the biomechanical evolution of human walking: approaches using predictive dynamic modelling**

R. Crompton, W. Weijie, University of Liverpool; W. Sellers, Loughborough University; L. Dennis, Nottingham University; Li Yu, University of Bristol

Traditional methods for reconstructing the locomotor adaptation of species known only from the fossil record analogize from the locomotor behaviour of living species which share a given morphological feature with the extinct species in question. Since the morphology of extinct species is by definition a compromise adaptation to the multiple demands placed on it by an environment which no longer exists, this is an unreliable approach. Further, no single living species is likely to show the same set of morphological features as a fossil species, which nevertheless can (by virtue of its very presence in the fossil record) be assumed to represent a successful adaptive response to its environment. Our group has pioneered a whole-body, reverse-engineering approach to reconstruction of the hominid fossil record, which assesses the likely behavioural repertoire of human ancestors on the basis of the mechanical energy costs of alternative hypothesized behaviours, calculated, as far as possible, from the proportions of the whole body. Inverse dynamic models are verifiable by predicting ground reaction forces (GRFs) for a known individual, and for a set of kinematics drawn from a performance of that individual for which GRFs were recorded. A further advantage is that costs may be compared for alternative sets of body proportions as well as sets of kinematics. Forwards dynamics approaches (predicting kinematics from muscle contraction patterns) are also used to predict the kinematics which incur the minimum metabolic energy cost; and allow us to predict internally partitioned contact forces and stresses from foot geometry.

#### **A5.11—Organisms moving in fluids: experimental approaches to studying kinematics and hydrodynamics**

G.V. Lauder, Organismic and Evolutionary Biology, Harvard University

Studying aquatic locomotion in organisms necessitates knowledge of body and appendage kinematics as well as patterns of water flow induced by oscillating propulsors. In this paper I provide an overview of recent approaches to studying organismal kinematics and experimental hydrodynamics. Kinematic data are most often acquired via high-speed video. Newly available video systems have significantly higher resolution and frame acquisition rates (e.g., 1280 by 1024 pixels per frame, at 500 frames per second) than previous equipment, and have considerably increased our ability to quantify body and appendage movement patterns. An example of locomotion in larval zebrafish is given to illustrate the utility of new high-resolution video in permitting analyses of gliding behavior and fin movements not possible with previous video systems. Experimental hydrodynamics of aquatic locomotion has been studied recently using digital particle image velocimetry (DPIV) which allows visualization of flow generated by the body and appendages. DPIV can be accomplished using relatively low-cost continuous wave lasers to illuminate two-dimensional planar slices of flow seeded with small reflective particles. Using high-speed video to image light reflected from these particles allows greater temporal resolution of wake flow patterns than use of standard 30 Hz digital cameras. Three examples of recent DPIV analyses of fish swimming will be presented: (1) pectoral fin wake flow patterns during steady swimming, maneuvering, and braking in trout and sunfish, (2) a new 'ring-within-a-ring' vortex structure in the wake of swimming spiny dogfish sharks, and (3) unexpected dorsal fin wake patterns in swimming trout.

#### **A5.12—From measured markers to modelled degrees of freedom**

E. Otten, Movements Sciences, University of Groningen; A. Hallems, Laboratory for Functional Morphology, University of Antwerp

The problem of obtaining joints angles and segment positions of an organism from optical motion capture data consists of four sub problems: The choice of number and location of optical markers; the choice of the multi-joint model of the organism at hand; the choice of angular and positional offsets of the model relative to the markers and finally the mathematical procedure to reconstruct joint angles and segment positions and orientations. The choices on markers and model topology are strongly connected. The choice of angular an posi-

tional offsets of the model relative to the markers can be solved by superimposing the model in transparency over digital photographs of the organism fitted with the markers and visually adjusting the model until optimal coverage is reached. The ensuing mathematical procedure is to create a segment attached local co-ordinate system based on at least 3 markers per segment. Then to calculate cardanian angles in continuity with the former timeframe. After that offsetting the position and/or orientation of this system based on the offset choices made before, followed by back calculating the orientation of the co-ordinate system relative to the parent element and finally affixing the modelled segment to the parent segment in the correct orientation.

A number of measurements and models will be used of the human body to illustrate the problems at hand.

### A5.13—Estimating the Mechanical Work of Locomotion

A.E. Minetti, Centre for Biophysical and Clinical Research into Human Movement, Manchester Metropolitan University, UK

The classical approach (Cavagna and Kaneko, 1977), namely to partition the total work ( $W_{TOT}$ ) into an external part,  $W_{EXT}$ , accounting for the (potential, PE, and kinetic, KE) energy changes of the body centre of mass (BCOM) with respect to the environment, and the internal work ( $W_{INT}$ ), accounting for the kinetic energy ( $KE_i$ ) changes of body segments (i) with respect to BCOM, has been a good working approximation so far. However, it is also known that  $W_{EXT}$  and  $W_{INT}$  cannot always be considered as two separate entities.  $W_{TOT}$ , being equal to  $W_{EXT} + W_{INT}$ , would represent the upper limit of the range of estimates where the 'true' mechanical work should lay. The lower limit would be  $W_{TOT}^*$ , another estimate of the total mechanical work where energy curves (PE, KE and  $KE_i$ ) are summed together before calculating the overall energy increases. This approach allowed new interpretations of human walking optimal speed, seen as the one where the movements of the limbs least interfere with BCOM, and horse bouncing gaits, where  $W_{TOT}^*$  is very similar to  $W_{EXT}$ , indicating that limbs  $W_{INT}$  is kept strategically low (Minetti 1999). The metabolic demand of locomotion includes also the cross-bridges cycling occurring during quasi-isometric activity, which produces no mechanical work. A measure of the 'EMG cost' of locomotion, done by weighing the contribution of the major muscle groups, could potentially provide a better approximation of the metabolic cost. A first example of this technique has

been recently put forward by Prilutsky and Gregor (2001).

#### REFERENCES

- Cavagna G.A., Kaneko M. Mechanical work and efficiency in level walking and running. *J. Physiol.* 268: 647–681, 1977
- Minetti A.E. The relationship between mechanics and energetics of locomotion. XVIIth Congress of the International Society of Biomechanics, Calgary, 1999.
- Prilutsky, B.I., Gregor, R.J. Swing- and support-related muscle actions differentially trigger human walk–run and run–walk transitions. *J. Exp. Biol.* 204, 2277–2287, 2001.

### A5.14—Experimenting on wood for tree biomechanics, some highlights of field and laboratory techniques

B. Thibaut, CNRS, University of Montpellier 2

Wood is the adaptive material for tree building. Experimenting on wood when looking at the mechanical aspects of tree ontogeny addresses 3 main topics: i) the role of wood as a material to assume mechanical integrity of plant against loads; ii) active pre-stressing as a way to ensure long term morphology and to react to changes in the environment; iii) a posteriori interpretation of the 'mechanical history' of trees via the occurrence of reaction wood. Materials strength is based on the relationships between strains and stresses where modulus of elasticity and stress at rupture are basic concepts. Non-destructive methods can be used in the field or in the lab for MOE estimation but not for rupture strength. Good correlations between these two properties can be used for indirect estimations. Residual stresses can only be calculated through strain measurement induced by local stress release. Hole-drilling or groove-cutting methods combined with strain gauges (or displacement transducers) are commonly used on standing trees, while tests on excised board segments can be carried out in the laboratory. Growth stresses inside woody plants are the result of the cell wall differentiation process. The level of these stresses are linked to local wood microstructure. Structural analysis, often at the cell wall level, is a powerful tool for investigating the past history of maturation strains within a plant axis. These tests can only be carried out in the lab although quasi non-destructive techniques such as increment core observation can be used for first level approximations in the field.

### **A5.15—Assessing bending and torsional mechanical properties of plant stems under field conditions**

N. Rowe, CNRS, Montpellier; T. Speck, Freiburg University; F. Gallenmüller, Freiburg University

In recent years we have used a variety of techniques to measure the bending and torsional properties of different plant growth forms in their natural habitats. We have developed a range of equipment which will be sure to work under extreme field conditions particularly in tropical rain forest in South America and remote semi-arid locations in Madagascar. We present equipment for carrying out 3- and 4-point bending tests in which a series of weights are manually applied to the tested stem and the deflections measured via a mounted dissecting microscope. Torsion tests are carried out on a portable torsion balance in which torques can be applied to plant stems via a range of specially manufactured spring-loaded cylinders. During each test the cylinder is rotated in cumulative steps and the deflection angle observed directly from the graduated cylinder. We discuss the exact protocols and the advantages and disadvantages of the different types of tests in addition to some of the problems encountered particularly in holding and fixing tested specimens.

### **A5.16—Experiments on pollination mechanisms and staminal lever arms in the genus *Salvia***

T. Speck, Botanical Garden, University of Freiburg; R. Claßen-Bockhoff, Botany, University of Mainz

For an integrative understanding of the importance of flower structures, staminal lever mechanics and exact pollen positioning for reproductive isolation and speciation in *Salvia*, the interaction between pollinators and flowers are studied. One aspect is the biomechanics of the staminal lever, its functioning and diversity. By means of a custom made device, allowing to measure forces in the milli-Newton range in intact flowers, forces and energies, necessary to move the staminal lever are measured in different *Salvia*-species (cf. Speck et al., 2003: The potential of plant biomechanics in functional biology and systematics. In Stuessy, Hörandl & Mayer (eds.), Deep Morphology: Toward a Renaissance of Morphology in Plant Systematics. Koeltz, Königstein).

A second aspect is related to the pollinators which are insects and humming-birds. In our experimental approach we concentrate on insect pollinators, as bees and bumble-bees. In the first set of experiments we have started to study if the forces and energies required to get to the nectar during the visit of a *Salvia*-flower are relevant for the foraging behaviour of the pollinators. For this purpose, the insects are trained to ‘artificial flowers’ with sugar water as food source, and the forces and energies, which are exerted by the insects in order to get to the food source are determined. The exerted forces and required energies are compared to the forces and energies necessary for the movement of the staminal levers and for the deformation of the flowers in *Salvia* which are necessary to get access to the nectar.

### **A5.17—Studying the biomechanics of locomotion under field conditions**

A.M. Wilson, T.H. Witte T. Pfau (The Royal Veterinary College)

Most biomechanics studies are undertaken in the laboratory during runway, treadmill, wind tunnel or flume locomotion. These techniques are excellent for instrumentation and study of exercise under controlled conditions but it is often useful to validate such measurements, where possible, under more natural conditions. Infra-red based motion analysis outdoors is difficult and video analysis offers limited resolution and calibration difficulties. Satellite GPS systems will determine speed and position accurately and some systems will track movement with centimetre accuracy five times per second on anything that can carry a substantial GPS antenna. Use of sensors such as accelerometers, gyroscopes and earth magnetic field sensors make the application of inertial based motion analysis systems possible if the signal processing challenges of double integration for position can be accomplished.

Collection of data from sensors also presents a challenge; data logging is becoming increasingly easy with modern microcontrollers and the bandwidth of radio-telemetry is improving. Wireless networking and DECT standards can sometimes offer ready built systems at a fraction of the cost of bespoke commercial units.

Assessment of metabolic cost is still difficult – labelled water techniques are only suited for long term studies. Portable systems for measuring oxygen consumption do exist but their complexity and cost makes attachment to animals stress inducing for all. Measurement of heart rate, duty factor and centre of mass movement all however provide indirect but useful measures.

**A5.18—Island radiation and Secondary evolution of self-supporting growth forms in the lianescent group Secamonoideae (*Apocynaceae s.l.*): Phylogeny, Biomechanics and development**

R. Lahaye, Biology, University of Toulouse III; L. Civeyrel, Biology, University of Toulouse III; N. Rowe, Biology, University of Montpellier; T. Speck, University of Freiburg

Island radiation and Secondary evolution of self-supporting growth forms in the lianescent group Secamonoideae (*Apocynaceae s.l.*): Phylogeny, Biomechanics and development.

We combine molecular phylogenetic approaches with biomechanical methods to explore the evolutionary transitions from twining lianas to 'shrub-like' forms. Many lianescent members of angiosperm families have probably evolved from self-supporting ancestors while the transition from lianescent forms back to self-supporting growth forms is apparently much rarer. We investigate a group of endemic Malagasy representatives of the Asclepiadaceae. Within this group, most species are lianescent but ongoing molecular phylogenies indicate several transitions to shrub-like growth forms. Biomechanical analyses indicate that such 'shrub-like' forms are not typical of self-supporting growth forms and show relatively minor variations in anatomy and development from the related lianas. These results suggest further evidence that in at least some groups of angiosperms, the evolution of lianescence possibly carries a high degree of developmental burden that limits subsequent evolution of diverse mechanical architectures.

**A5.19—Estimate impact energy dissipation in human heel pad during normal gaits**

K.-J. Chi, Biology, Duke University; D. Schmitt, Biological Anthropology and Anatomy, Duke University.

The human heel pad is considered an important structure to attenuate the transient force due to foot–ground impact. Although the mechanical properties of heel pads have been reported, the mechanical energy involved during foot–ground contact has never been investigated. This study describes a new, in vivo approach to estimate the dissipation of mechanical energy during heel strike in walking and running. To this end, the effective foot mass during impact phase was obtained empirically using the impulse–momentum equation. We simultaneously collected the force exerted on the heel pad, pad deformation, and body motion during impact phase of barefoot walking, running, and crouched walking. The latter was included to examine the effect of knee angle on the effective foot mass. The magnitude of the effective foot mass as a percentage of body mass (BM) varies with knee angle at impact and significantly differs among gaits: 10.57% BM in walking, 7.53% BM in running, and 5.93% BM in crouched walking. At the instant prior to heel strike, the total mechanical energy ranges from 0.32 to 4.95 J, 62% of which is used to do work to deform the pad, while 38% is dissipated. By studying heel pad during the impact phase, we observed that the rear region of the pad is loaded at heel strike during walking and running. Our results suggest that the heel pad shows spatial variation in its mechanical properties—more energy is dissipated when the rear region of the pad is loaded.