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Analysis

Bioenergetics of Animal Locomotion: Lessons for Expedient Monitoring in Human Fitness and Weight Management

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Basic principles of animal physiology can provide valuable insights to complex systems. Such is the case with foot–ground contact time (T_c) and bioenergetics. Modeling energy costs of human movement is complicated, requiring articulated models to account for biomechanical efficiencies, elastic elements that cyclically store and release energy, and the various groups and types of muscles appropriate to the type of locomotion. However, overarching principles governing the metabolic cost moving a body mass through space and time suggest total mass (body weight and load weight) and T_c (the time during each step that the foot is in contact with the ground) present a much simpler solution to estimating the energy costs of locomotion. Reed Hoyt and Peter Weyand applied an empirical observation that the metabolic cost of walking or running varied as a function of the ratio of body weight (Wb) and T_c to estimate the metabolic costs of walking or running (M_{loco}).[1] In this issue of *DT&T*,[2] the T_c technique for estimation of M_{loco} has undergone further validation for use in free-ranging humans moving over level ground at different speeds. For an extra challenge, these tests involved Marines carrying backpack loads in rigorous training.

The idea for this measurement approach came from studies at Harvard University's Concord Field Station in Bedford, MA, where cross-species studies seek to improve our understanding of the principles of biomechanics and bioenergetics from the cell and tissue level to whole organisms. Energy expenditure and locomotor mechanics have been measured for terrestrial birds, mammals, and even some reptiles with a wide variety of locomotory strategies, ranging from tiny kangaroo rats running on a treadmill to trotting elephants accompanied by a golf cart modified to collected gas expired from the elephant's trunk. All of the animals tested fall in on a single curve relating mass, T_c, and energy expenditure; locomotion is more economical with increasing mass of various species, no matter how ungainly some larger creatures may seem.[3] The Concord Field Station investigators observed that the same size dependence they initially quantified for the rate of metabolic energy expenditure also applied to the rates at which the different-sized animals completed their strides. For example, at equivalent speeds such as the trot–gallop transition where the relative proportions of the contact and aerial portions of the stride are the same, the per-stride costs of the large and small creatures are also the same. This observation raised the possibility that the greater mass-specific metabolic rates of smaller animals might be a direct function of the shorter periods of their strides. The Concord Field Station crew considered the likely candidate to be the con-

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tact portion of the stride during which ground force must be applied to support the body's weight. Subsequent investigation demonstrated this was indeed the case. Regardless of the animal's size or speed, mass-specific metabolic rates are a constant multiple of the inverse period of foot–ground contact that the investigators used to estimate the rate of ground force application.[4] This led to the understanding that on level ground, the primary metabolic costs are those required for the muscles to support body weight.[5] The T_c method is increasingly accepted,[6] and is well suited to field application because the equation requires only two inputs: body weight and T_c ($M_{loco} = Wb/T_c \times$ Constant).

The actual measurement device first devised by Hoyt and co-workers measured T_c using force-sensitive resistors under the toe and heel and was validated with treadmill walking and running.[7] Field tests of the prototype hardware were disheartening. The initial conceptions required an imprint of each soldiers' foot so that special insoles could be constructed to house an inside-the-boot monitor. A collaborative field trial was conducted with Norwegian cadets going through an extreme endurance course. Wires to the connectors broke, data downloads failed, and the inserts proved to be an irritant to the subjects. These technical problems were solved without international incident, and eventually led to the accelerometric outside-the-boot lace-up prototype footstrike monitor. This has since been used in a variety of military physiological monitoring studies along with other sensors such as the wrist-worn actigraph to complement sleep/wake history in studies such as one of senior military leaders involved in high-intensity military planning activities, and another study involving a squad of infantry soldiers in a field training exercise.[8]

In this latest validation test by Hoyt et al.,[2] activity periods were classified into categories of locomotion that determined the method of energy estimation. The metabolic cost of running and walking were estimated from total weight and the time between the detection of heel strike and toe off (foot down/foot up). Slow walk was detected by a heel strike with no detectable toe off, with energy costs estimated from some assumptions about T_c. Shuffle [or "non-exercise activity thermogenesis" (NEAT)] periods were detected by accelerometer activity without discernible heel or toe activity, with energy costs estimated as the metabolic cost of standing. Rest was when no accelerometer activity was present and no additional energy costs beyond resting metabolic rate (RMR) were estimated. These estimates were summed to estimate total M_{loco}. Comparisons were made to total daily energy expenditure (TDEE) measured using doubly labeled water (DLW) ($^2H_2{}^{18}O$). To do this, the investigators had to estimate the missing components of TDEE that are not estimated from M_{loco}, including RMR and thermic effects of food (TEF). Although follow-up studies are certainly needed, and a number of assumptions were required to make this comparison, the results were quite good with the mean error in TDEE between T_c and DLW estimated at 12%. This was a highly active group with relatively little sleep time, and average energy expenditure of 15.3 MJ/day (3,670 kcal/day) over the 50-h period of their exercise. This also included average carried weights of 30 kg (also factored into the total mass for T_c computations).

There are numerous gadgets now marketed for energy expenditure measurements with a variety of uses and usefulness. One should clearly distinguish the components of metabolic costs that the methods attempt to measure. Portable calorimeters that have a breathing apparatus and a backpack gas analyzer provide estimates of total energy expenditure, including those components associated with locomotion. These have been used to assess metabolic costs associated with various typical soldier tasks such as carrying stretchers and carrying backpack loads in various types of constricting clothing, etc. This method is estimated to provide accuracy within 5% alongside of treadmill testing for $\dot{V}O_{2\,max}$.[9] Heart rate, calibrated to the individual, provides some reasonable estimates of total energy expenditure in discrete time periods but can be unreliable in largely sedentary populations. Both calorimetry and heart rate reflect something about overall metabolic rate, combining RMR, TEF, NEAT, and energy costs of activity (including locomotion). Pedometry, accelerometry, and T_c

measurement each provide estimates of metabolic costs associated with body motion. The type of activity captured obviously depends on the location of the sensors. Standard pedometry, in which only a step count is recorded, is one of the least reliable of energy measurement methods and provides more value as a motivational tool for patient exercise than a useful energy measurement device. However, accelerometer-based pedometers capable of reliably recording time series data over days appear to be scientifically useful.[10] Accelerometry has been used primarily on wrists and hips to estimate overall body motion energy expenditure and may work best in combination, as described in the last issue of *DT&T*.[11] Compared with measures of oxygen uptake in a laboratory, commercially available accelerometers have been reported to have errors averaging 10–20%; much better accuracy was reported by Chen et al.,[11] who used multiple accelerometers. The T_c method provides an alternate path to accurately estimate muscle force generation and M_{loco}, making it potentially more accurate for measurement of this specific component; upper body motion captured by multiple accelerometers or heart rate techniques is not measured with this approach. There is great value in assessing weight-bearing exercise, as the most important component of fitness and weight management programs, as well as for specific exercise objectives such as stimulating bone mineral accretion. As Hoyt et al.[2] point out, this may also provide a novel approach to estimating NEAT, a potentially important factor in weight management.

In future developments, if high-tech accelerometer-based pedometers capable of recording data over days could be coupled with a tri-axial accelerometers or supersensitive altimeters to detect movement up or down inclines, including ladders and stairs, this might resolve some variability expected from work on uneven surfaces. Technologies that put the sensor back inside the shoe to measure regional pressures on the foot ("pedobarography") may also provide very useful information for noninvasive monitoring of energetics of locomotion, with a complete picture of type of activity as well as ground reaction forces involved.

The research effort on locomotion continues with Department of Defense-supported research in Peter Weyand's lab at Rice University. One hope is that this type of research will provide a basis for a non-running test of fitness that could be applied both to the military and to patients with diabetes, providing a simple and accurate method to assess overall changes in physical fitness levels. As an example, Weyand, Hoyt, and colleagues recently reported that combining T_c with heart rate monitoring produced accurate estimates of maximal aerobic power.[12] It would be useful to know if changes in T_c and heart rate relationships over periods of stable monitoring taken weeks or months apart could reflect changes in fitness levels, or if acute alterations during military field operations might provide an index of thermal or dehydration. Providing noninvasive "smart shoe" technologies that provide feed back about energy expenditure as well as improvements in fitness could encourage soldiers and patients with diabetes to engage in physical training programs.

REFERENCES

1. Hoyt RW, Weyand PG: Advances in ambulatory monitoring: using foot contact time to estimate the metabolic cost of locomotion. In: Carlson-Newberry SJ, Costello RB, eds. Emerging Technologies for Nutrition Research. Washington, DC: National Academy Press, 1997:315–343.
2. Hoyt RW, Buller MJ, Santee WR, Yokota M, Weyand PG, DeLany JP: Total energy expenditure estimated using foot–ground contact pedometry. Diabetes Technol Ther 2004;6:71–81.
3. Langman VA, Roberts TJ, Black J, Maloiy GMO, Heglund NC, Weber J-M, Kram R, Taylor CR: Moving cheaply: energetics of walking in the African elephant. J Exp Biol 1995;198:629–632.
4. Kram R, Taylor CR: The energetics of running: a new perspective. Nature 1990;19:265–267.
5. Taylor CR: Force development during sustained locomotion: a determinant of gait, speed and metabolic power. J Exp Biol 1985;115:253–262.
6. Sih BL, Stuhmiller JH: The metabolic cost of force generation. Med Sci Sports Exerc 2003;35:623–629.
7. Hoyt RW, Knapik JJ, Lanza JF, Jones BH, Staab JS: Ambulatory foot contact monitor to estimate the metabolic cost of human locomotion. J Appl Physiol 1994;76:1818–1822.
8. Hoyt RW, Buller MJ, Redin MS, Poor RD, Oliver SR, Matthew WT, Latzka WA, Young AJ, Redmond D,

Kearns C: Technical Report T98-6 (AD A332713): Soldier Physiological Monitoring—Results of Dismounted Battlespace Battle Lab Concept Experimentation Program Field Study. Natick, MA: U.S. Army Research Institute of Environmental Medicine, 1997.

9. Patton JF: Measurement of oxygen uptake with portable equipment. In: Carlson-Newberry SJ, Costello RB, eds. Emerging Technologies for Nutrition Research. Washington, DC: National Academy Press, 1997:297–314.
10. Schneider PL, Crouter SE, Lukajic O, Bassett DR: Accuracy and reliability of 10 pedometers for measuring steps over a 400-m walk. Med Sci Sports Exerc 2003;35:1779–1784.
11. Chen KY, Acra SA, Majchrzak K, Donahue CL, Baker L, Clemens L, Sun M, Buchowski MS: Predicting energy expenditure of physical activity using hip- and wrist-worn accelerometers. Diabetes Technol Ther 2004;6:1023–1033.
12. Weyand PG, Kelly M, Blackadar T, Darley JC, Oliver SR, Ohlenbusch NE, Joffe SW, Hoyt RW: Ambulatory estimates of maximal aerobic power from foot-ground contact times and heart rates in running humans. J Appl Physiol 2001;91:451–458.

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