Application of Power/Energy Analysis in 3D

Dr. Chris Kirtley MB ChB, PhD', Chris A McGibbon PhD'', Redha Taiar PhD'
'STAPS, University of Reims, Champagne, France and ''Dept. Of Kinesiology, University of New Brunswick, Canada
ckirtley@gmail.com

***Abstract*—Mechanical power measures are probably the most contentious biomechanical variables. They were originally defined and derived from 2D models, and subsequent extension to 3D raises several controversial issues. Moreover, power (or more correctly, energy) flow analysis is still not performed routinely by commercial motion analysis software. An overview is presented here with the aim of stimulating a fruitful discussion and consensus.**

Keywords-power; energy; generation; absorption; transfer

I. Introduction

Power analysis can be confusing, not least because of the inconsistent terminology used by many researchers (Table 1).

Of all these measures, most commercial 3D motion analysis systems report only the first, which is a shame. Joint power, whilst certainly being useful, reveals only a small part of the total picture [1]. The term 'passive flow' describes the flow of power (or more correctly energy) through the joint itself, while 'active flow' indicates transfer by the muscles spanning the joint (fig. 1).

Muscles are fundamentally capable of two functions [2]:

- Generate or absorb energy (concentric or eccentric contraction)
- Redistribute energy between segments.

Name	Derivation	Equation	Interpretation
Joint or muscle power	Joint moment × joint angular velocity	$M\omega_{joint}$ or $M(\omega_{proximal} - \omega_{distal})$	Power generation or absorption by muscle at the joint
Passive flow	Joint reaction force × joint linear velocity	Fv_{joint}	Power flow into a segment through a joint
Active flow	Joint moment × segment angular velocity	$M\omega_{segment}$	Power flow into a segment from a muscle
Total joint power flow	Sum of the passive and active power flow at a joint	$Fv_{joint} + M\omega_{proximal} + M\omega_{distal}$	Shows direction and magnitude of power flow at a joint
Segmental power	Sum of the passive and active power flow at each end of the segment	$Fv_{proximal} + M\omega_{proximal} + Fv_{distal} + M\omega_{distal}$	Total power flow into segment
Instantaneous segment power (or rate of energy change)	Change in segment energy with time, dE/dt	$d(mgh_{segment} + \frac{1}{2}mv^2_{segment} + \frac{1}{2}I\omega^2_{segment})/dt$	Total power of a segment at a given time
Power balance	Instantaneous power – power flow	$dE/dt - Fv_{proximal} - M\omega_{proximal} - Fv_{distal} - M\omega_{distal}$	Should be zero if power calculations are correct

Table 1: Terminology used for various power measures

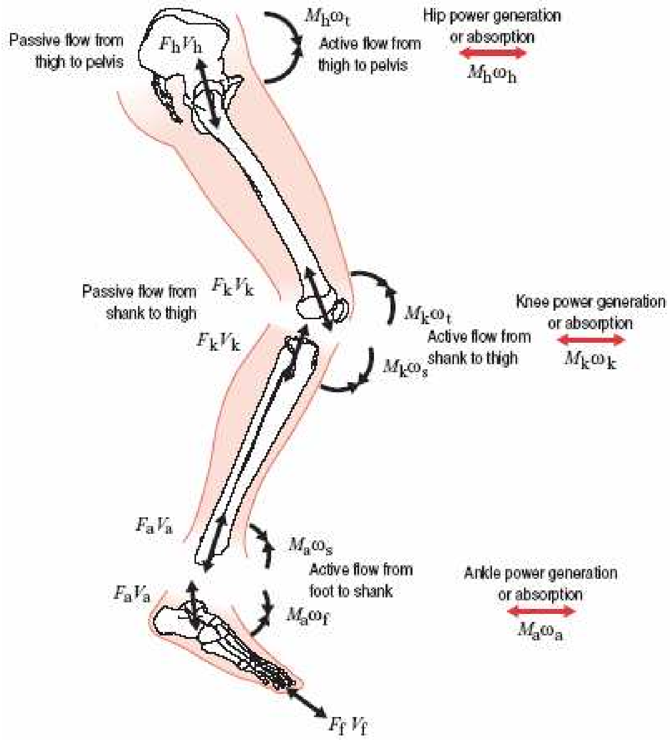

Fig. 1: Power (energy) flows between lower-limb joints

At the joint, this power is calculated by the moment multiplied by the net angular velocity of the segments being moved, the sign of the product indicating generation (+) or absorption (–):

$$\text{Power generation or absorption at joint} = M\omega_{joint}$$

If the angular velocity is zero, there is no power generated or absorbed: in other words an *isometric* contraction. Note that joint power, ω_{joint} is the same as ($\omega_{proximal} - \omega_{distal}$), so the equation can also be written:

$$\text{Power} = M\,(\omega_{proximal} - \omega_{distal})$$
$$\text{or Power} = M\,\omega_{proximal} - M\,\omega_{distal}$$

In other words, the power flowing through the muscle has two components – one part delivered to, or drained from, the proximal segment, and one delivered to, or drained from, the distal segment. These are termed the *active* flows to the segments because they arise directly from the muscles attached to the segments at that joint.

When the proximal flow exactly equals the distal flow ($M\omega_{proximal} = M\omega_{distal}$) there is no power generated or absorbed. In other words, the muscle must be contracting isometrically, and is merely transferring power from one segment to the other. On the other hand, in a situation where one segment is fixed (e.g. the foot flat on the floor) there will be power generation/absorption but no transfer to that segment. In most cases, some combination of transfer and generation/absorption occurs.

The algorithm to calculate energy flow is thus:

$$\text{if } \omega_{proximal} * \omega_{distal} > 0 \text{ then}$$
$$(\text{if } |\omega_{proximal}| > |\omega_{distal}| \text{ then } P = M\omega_{distal} \text{ else } P = M\omega_{proximal})$$
$$\text{else } P = 0$$

II. 3D CONSIDERATIONS

A number of additional considerations arise when power measures are applied to a 3D model.

Scalar nature of Power

Since power is a scalar quantity, it is arguable whether the components of power (energy) should be considered separately or combined into a "total power" measure. Currently there is no consensus – some laboratories (perhaps the majority) report total power (fig. 2), whilst others report the individual flexion/extension, ab/adduction, transverse components (fig. 3).

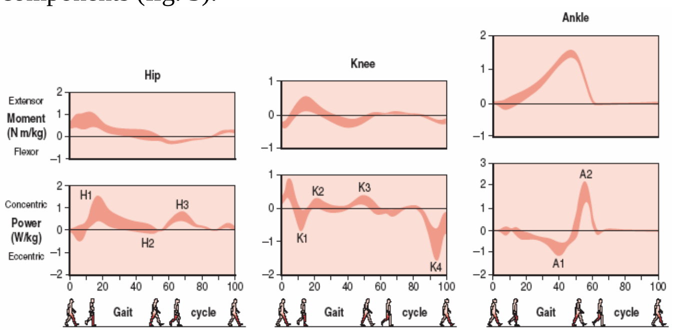

Fig. 2: Gait analysis report using total joint power

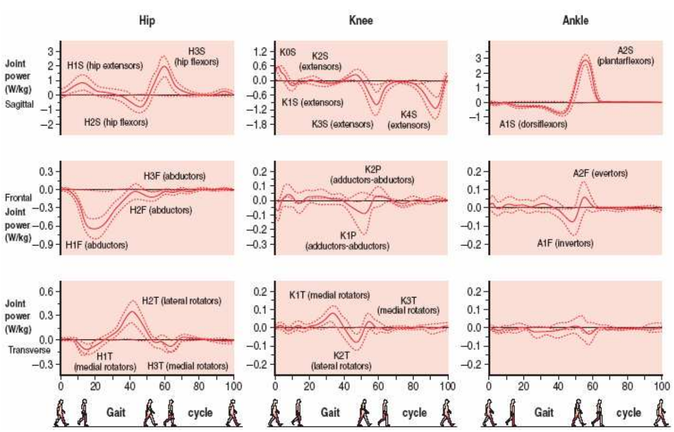

Fig. 3: Gait report presenting power in three orthogonal planes

Coordinate Systems used

Joint moments calculated by commercial motion analysis systems are usually expressed in an orthogonal segment-fixed XYZ reference frame, or in a global reference frame. To use these for power calculations, therefore, the segment angular velocity vectors must also be expressed in the same reference frame. 3-D kinematic analysis results in a rotation matrix R that describes the relative orientation between the two segments. The angular velocity vector $\omega = (\omega_x, \omega_y, \omega_z)$ can be estimated from R and its time-derivative Ŕ:

$$\begin{pmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{pmatrix} = \mathrm{inv}(R) * \acute{R}$$

Joint power is simply the dot product of M and ω: $P = M_x . \omega_x + M_y . \omega_y + M_z . \omega_z$, which can be interpreted as flexion, abduction, and transverse rotation power.

III. INTERPRETATION

The following questions now arise

- What additional insights can be gained from performing a 3D power/energy analysis?
- How valid would such analyses be in the practical/clinical situation?
- How best can the results be presented/interpreted?
- How would such an analysis be applied?

A. Insights

Despite the high cost and labour-intensive nature of modern 3D analysis, the interpretation of the results remains very subjective. Power/energy analysis offers additional insights and thus provides an opportunity to reduce or eliminate such subjectivity.

B. B. Validity

Clearly, if it is going to be applied routinely, power/energy analysis will need to be validated. This will require standardization and consensus on the issues discussed above. Furthermore, the derivations involve more assumptions and incorporate many more biomechanical variables than simpler terms such as joint angle and moment. Fortunately, a method exists by which the accuracy of the calculations can be tested. If these are correct, the power entering a segment ought to equal the power leaving it – the so-called "power balance" [5-8].

C. C. Presentation and interpretion

There is a natural reluctance to add further information to an already complex 3D report. The standard gait analysis has therefore historically been limited to joint angles, moments and powers. Such a set of curves already embodies a surfeit of information that is difficult to interpret. Yet it further relies

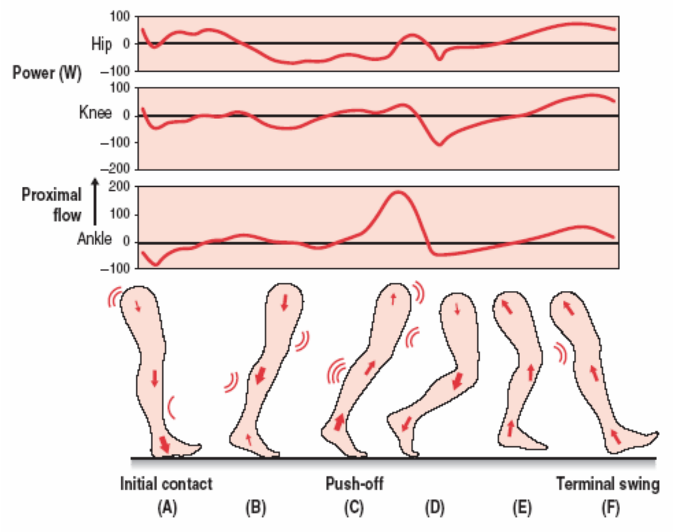

Fig. 4: Example presentation of energy flow. The size of the arrows is roughly proportional to the magnitude of the power flow, and major power generation (convex) and absorption (concave) are indicated by arcs over the active muscle group [9].

on a large body of experience, which is inevitably incomplete and contaminated by personal perception and prejudice. Power analysis offers the potential to demystify the report by presenting the information in a more intuitive format (fig. 4).

CONCLUSIONS

These issues will be illustrated by clinical examples which will hopefully stimulate discussion in order to arrive at a consensus about the future direction of 3D power/energy analysis.

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REFERENCES

[1] Quanbury A O, Winter D A, Reimer G D 1975 Instantaneous power and power flow in body segments during walking. Journal of Human Movement Studies 1:59–67

[2] Zajac F E, Neptune R R, Kautz S A 2002 Biomechanics and muscle coordination of human walking. Part I: Introduction to concepts, power transfer, dynamics and simulations. Gait & Posture 16:215–232

[3] Winter D A, Robertson D G 1978 Joint torque and energy patterns in normal gait. Biological Cybernetics 29:137–142

[4] Sadeghi H, Allard P, Duhaime M 2000 Contributions of lower-limb muscle power in gait of people without impairments. Physical Therapy 80(12):1188–1196

[5] Winter D A 1990 Biomechanics and motor control of human movement, 2nd edn. Wiley, New York.

[6] McGibbon CA, Krebs DE. The influence of segment endpoint kinematics on segmental power calculations. Gait Posture. 1998;7:237-242.

[7] Buczek FL, Kepple TM, Siegel KL, Stanhope SJ. Translational and rotational joint power terms in a six degree-of-freedom model of the normal ankle complex. J Biomech. 1994;27:1447-1457.

[8] Siegel K L, Kepple T M, Stanhope S J 2004 Joint moment control of mechanical energy flow during normal gait. Gait & Posture 19(1):69–75

[9] Kirtley C 2006 Clinical Gait Analysis, theory and practice. Oxford, Elsevier.