GAIT ANALYSIS REVISITED: THE MOTION OF THE BODY CENTRE OF MASS MAKES THE MOTION OF BODY PARTS MEANINGFUL

NOV POGLED NA ANALIZO HOJE: GIBANJE TEŽIŠČA TELESA OSMIŠLJA GIBANJE TELESNIH DELOV

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Abstract

Scientific knowledge of kinematic, dynamic and neural parameters of gait is very deep, but its clinical application has been comparatively scarce. The gap between mere description and interpretation can be bridged by looking at the motion of the body system as a whole, not only at the motion of its segments, whereby the body system can be represented by its centre of mass (CM). The basis for this approach is the work of Giovanni Cavagna and coworkers on the motion of the CM during walking. The paper reviews its applications aimed at clarifying the meaning of various impairments in terms of pathology and compensation. The "forced use" exercise paradigm is presented as opposed to the conventional exercise that induces "learned non-use". Recent developments in this field are outlined, such as the dynamic and static balance testing platforms and the finding regarding three-dimensional motion of the CM during a stride. The latter are useful to explain falls. Future research should be directed towards simultaneous recordings of the CM and the segmental motions, and the study of the CM motion in response to various treatments and/or orthotic/prosthetic appliances.

Key words:
gait analysis, motion, centre of mass, Cavagna paradigm, lower limbs, learned non-use, forced use, stride

Izvleček

Znanstveno poznavanje kinematike, dinamike in živčne aktivnosti pri hoji je temeljito, a njegova uporaba v klinični praksi je razmeroma slaba. Razkorak med opisom in razumevanjem je moč premostiti z opazovanjem gibanja telesa kot celote, ne le njegovih delov, pri čemer telo kot celoto predstavlja težišče. Osnova za tak pristop je delo Giovannija Cavagne in sodelavcev o gibanju težišča pri hoji. Prispevek povzema primere uporabe tega pristopa, ki razjasnjujejo pomen različnih okvar z vidika patologije in kompenzacije. Predstavljena je paradigma »prisilne uporabe« kot nasprotje običajnega razgibavanja, ki povzroči »naučeno neuporabo«. Naštete so novejše raziskave s tega področja, ki vključujejo dinamične in statične plošče za testiranje ravnotežja ter spoznanja o trirazsežnem gibanju težišča med dvojnim korakom. Slednje je uporabno za pojasnjevanje padcev. Prihodnje raziskave bodo usmerjene v sočasno spremljanje gibanja težišča in odsekov udov ter v preučevanje gibanja težišča po različnih terapijah oziroma uporabi ortoz in protez.

Ključne besede:
analiza hoje, gibanje, težišče, pristop Cavagne, spodnji udi, naučena neuporaba, prisilna uporaba, korak

BACKGROUND

Human walking is usually studied from the perspective of the cyclic rotation of lower limb joints. Kinematic, dynamic and neural parameters (in practice, surface EMG recordings) are now the classic ingredients of gait analysis in many laboratories across the world. Since the early years of photography and (soon after) cinematography, great progress has been made in this field (1, 2).

A huge amount of information about the motion of body segments can be gathered in short sessions, with non-

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invasive and entirely wireless procedures. Knowledge of the physiology of gait is now very deep. The scientific community, however, perceives that the clinical fall-out has been comparatively scarce. A keen visual observation and the patient's perceptions are still the milestones for clinical decisions about drug or exercise prescription, and orthotic or prosthetic fitting.

THE CHALLENGE

The author contends that this happens because (a) the available technology may provide many answers but clinical medicine does not always pose the right questions, and (b) the technology provides a detailed description of what is happening but it cannot itself provide a clinical interpretation, i.e., a value judgement about what represents an original impairment and what represents a compensatory mechanism. Two common topics in clinical gait research – speed and energy expenditure, and motion asymmetries between the two lower limbs – serve as examples:

- Most of the Literature agrees that pathological gaits are "inefficient", because the cost (energy expenditure per unit distance) is increased. However, in a meta-analysis it was shown that even healthy subjects are "inefficient" if they walk at the lower speeds adopted by patients affected by the majority of impairments (3). There is an optimal speed form the point of view of "efficiency": the cost per unit distance increases both below and above such speed. Therefore, does "pathology" lie in a lower attainable speed (which might be the case for heart, respiratory or muscle weakness), or is this speed a way to attenuate intrinsic alterations of the walking mechanics (which might be the case in painful joints, weakness, ataxia, spasticity etc.)?
- In a variety of orthopaedic and neurologic impairments, the kinematics, the dynamics and the EMG sequences differ between the left and the right lower limb. Should we try to restore mobility, force and coordination in the "affected" limb, and ask for a more symmetric gait? Unfortunately, asymmetry may represent a compensatory mechanism minimising the ensemble of overall energy expenditure, insecurity, pain and/or weakness. If this is so, all efforts addressed to the affected limb are doomed to fail. In the author's opinion a neglected yet enlightening observation comes from the amputees using prostheses: their stump is always hypotrophic although one might expect a compensatory hypertrophy (4).

CAVAGNA'S PARADIGM

How then can we fill the gap between mere description and interpretation? The answer is: by looking at the motion of the body system as a whole, not only at the motion of its segments. The body system can be represented, from a mechanical standpoint, by its centre of mass (CM). The CM is unfamiliar, and it looks a weird object indeed, to most clinicians, because it does not correspond to any definite body part. It is a virtual point that can even lie outside the body system, like in the high-jump technique known as "Fosbury flop" when the CM stays beneath the crossbar while the body segments are curling above. Yet, at each instant the central nervous system must know where the CM is and predict where it will be. In some sense, in locomotion the movements of the body segments aim at displacing the CM of mass. Mostly thanks to the Italian physiologist Rodolfo Margaria (5) it is now clear that the CM moves, at each step, like an inverted pendulum, thus saving muscle work through the passive exchange between kinetic and gravitation potential energy. Margaria's pupil Giovanni Cavagna invented an ingenious method to record the motion of the CM during walking. The subject is requested to perform several steps over long force platforms, and the displacements of the CM are computed through simple equations (6). This is the so-called direct or "Newtonian" method, the gold standard against which indirect methods based on modelling of the kinematics of body segments (7) must be confronted. Cavagna and coworkers have been producing a huge amount of original information about this general mechanism of terrestrial locomotion shared by human adults and children and animals alike, and explaining differences in gait mechanics under Earth, sub- and hyper-gravity (8-10). The method allows one to compute the changes of kinetic (*Ek*) and potential "vertical" (*Ev*) energy of the CM. The increments represent mechanical work, *Wk* and *Wv*, respectively. Their sum, the total mechanical energy of the CM (Em_{tot}) should remain constant if the motion of the CM reflected a perfect pendulum-like oscillation. The energy exchange is not perfect, however, so that some increments of Em_{tot} are observed both during the double ("a" increment) and the single stance ("b" increment). The increments imply that the energy exchange is incomplete and that positive mechanical work (*Wext*) must be provided by muscles to keep the body in motion with respect to the ground (hence the "ext" suffix, meaning "external"). Of course energy is spent also to move the arms and the legs with respect to the CM, but this "internal" work does not contribute meaningfully to the displacement of the body system. The "efficiency" of the pendulum mechanism can be quantified through the so called "percent recovery", *R* (8):

$$R = 100 \times (Wk + Wv - Wext) / (Wk + Wv)$$

The smaller *Wext* is, the more the time courses of *Wk* and *Wv* are mirror images, like in an ideal pendulum. When computed along an entire step, *R* can reach 65 % at the optimal speed of about 4 Km hr^{-1} in healthy adults, which means a saving of 65 % of the muscle work needed if the energy exchange had not taken place. The instantaneous *R*, *Rinst*, can reach 100 % (see below) and even drop to 0 %. In the author's opinion, Cavagna's revolutionary approach has been tremendously underestimated in clinical research despite the growing evidence that looking at the motion of the CM may clarify the meaning (pathology vs. compensation) of many segmental impairments.

Following Cavagna's method it has been shown that in unilateral hip arthritis and hemiparesis *Wext* may be 3 to 5 times higher during the step performed by pivoting on the affected limb (11, 12) compared to the subsequent step, thus indicating a nearly passive "pole vault" over the impaired limb. Of course, extra muscular work was required from the sound limb. Interestingly, the overall *Wext* along the stride was normal. The same findings were replicated in further studies on amputees with above- and below-knee prosthesis. In these studies, the left-right oscillations of the CM were also measured, and the external power (work per time unit, *Wext*') during the "a" (double stance) and "b" (single stance) increments were computed. It was shown that most of the muscle power was spent during the double stance, and that *Wext'* was up to five times larger when the healthy side was on the ground in a rear position (4). The sound limb evidently provides most of the mechanical work and power needed to keep the body in motion, and it can only do so when it is in rear position thus "pushing" the body system to "pole vault" over the impaired limb. The overall muscle power output along the stride, however, may remain normal.

LEARNED NON-USE AND FORCED USE

These data confirm that gait asymmetries often represent a form of optimisation of the gait motion as a whole. In chronic conditions, conventional exercise approaches aiming at restoring the activity of the impaired limb are doomed to fail, given the "choice" for sparing the affected side, overloading the unaffected side, and keeping the overall energy expenditure within the physiologic range. This seems to hold regardless of the underlying impairment.

It was suggested that this represents a form of "learned non-use", which is well documented for other forms of asymmetric impairments such strabismus or upper limb paresis (13). In these conditions the constraints imposed on the sound side lead to "forced use" of the affected side which should improve its mobility. The efficacy of the "forced use" exercise paradigm is ascertained for the two-century old technique of eye patching in child strabismus, and is still under scrutiny for the upper limb paresis in stroke patients (14). Hence, a hypothesis was put forward that "learned non-use" also contributes to kinematic and dynamic gait asymmetries in unilateral lower limb impairments, and that "forced use" exercises may decrease the asymmetry (15). In the author's opinion, the hypothesis of "learned non-use" in unilateral gait impairments had not been proposed before because the affected lower limb actually moves, sometimes even with normal kinematics (cf. amputees with advanced lower limb prostheses), yet the kinetic symmetry may conceal a severe dynamic asymmetry which can be hardly appreciated through visual observation.

RECENT DEVELOPMENTS

Looking at the CM and not only at body segments may also enlighten the issue of balance during gait. Balance deficits are among the most frequent causes of gait impairments and falls. The instrumental assessment of balance is mostly left to posturography based on the measurements of the 2D horizontal oscillations of the body centre of pressure (a proxy of the CM) in various conditions (eyes open, eyes closed, soft support surfaces). More refined and challenging paradigms exist, such as the Sensory Organisation Test (SOT) performed on the EquiTest™ dynamic platform, or on the Balance Master™ static platform (16). During the SOT, the platform and/or the visual surround can oscillate "tuned" with the subject's fore-and-aft oscillations, thus leaving unchanged the ankle joint angle (i.e., foot proprioception) and/or the distance from the visual target. The static Balance Master™ platform and many other static platforms give estimates of the motion of the CM when the subject is requested to actively lean towards "targets" appearing on a PC screen and representing the limits of the base of support in various directiong. On both instruments balance is tested during standing, and the generalizability of results to actual walking remains to be established.

The 3D motion of the CM can be nicely described by expanding the Cavagna's paradigm. A direct description of the CM trajectory during a stride has been published (17). Apart from forward progression, the path of the CM has an elegant cyclic figure of "8" shape, some 4 cm wide and 2 cm long and high, which was named "bow-tie". The path length and shape are speed-dependent. Research on this intriguing summary of the whole body motion is still in progress. Recently, the dynamic features of the "bow-tie" were investigated (18). It appears that a fixed relationship exists between the tangential speed and the curvature of the trajectory, following a somewhat mysterious "power law" underlying many human motions (e.g. eye, upper limb, and tongue motions; see the references in (18) for a review). However, during walking the law only holds for most of the single stance phase, when the movement of the CM is purely ballistic (i.e. *Rinst* is very high, reaching 100 % in some cases). It was shown that when muscle energy has to be injected into the body system, the "law" is suspended and Rinst may drop to 0%. Interestingly, the "b" increment described for the sagittal motion of the CM embraces to the very short phase of the single stance when the "pendulum" is made to swing from left to right and vise versa; conversely, the curvature is maximal and for a time as short as 50 ms *Rinst* drops to 0%. Not surprisingly, it is known that most of the falls in unstable patients happen in the lateral direction. To sum up, the length, the shape, the speed/curvature and *Rinst* appear to be very promising parameters for interpreting the role of segmental motion in determining not only the cost, but also the overall stability of the CM trajectory.

FUTURE RESEARCH

The next steps of this approach privileging the CM over the body segments, i.e., the whole over the parts, will be the simultaneous recordings of the CM and the segmental motions, and the study of the CM motion in response to various treatments and/or orthotic/prosthetic appliances. These studies will hopefully lead to a definition of key variables to be analysed in distinct gait impairments, thus bridging the gap between description and clinical interpretation of research findings.

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