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The effects of gravity on human locomotion repertoire: Cost of transport & body centre of mass analysis

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Abstract

Human legged locomotion has been widely studied from both mechanical and bioenergetics points of view, however some aspects are still unaddressed and this thesis aimed to analysed some of them. One of the two methods for calculating muscular work during locomotion, which is an interesting parameters that can describe locomotion and subjective featuring, concerns the body centre of mass (BCoM) movements. The BCoM is the ideal point of the body where all forces act, and especially in a multi segment body as the human body, it is much easier and useful to calculate and follow its trajectory as the movement of the whole body. In order to compute BCoM two methods can be used: a double integration of the ground reaction forces, the forces exerted by feet when in contact to the ground, based on Newton's second law, which is considered the gold standard, and called Direct Dynamics; and the weighted mean of segments centre of mass (COM) obtained by motion analysis, called Inverse Dynamics. Segments mass and COM location are based on anthropometric tables, which are scaled on subjects' lengths; this is an approximation and assumes that segments are rigid, introducing potential errors. Even if there is not a complete 3D validation of Inverse Dynamics as a function of speed in the human gaits, Inverse and Direct Dynamics are often used interchangeably. In the first part of the thesis Inverse and Direct Dynamics in the human locomotion repertoire were compared in order to analyse different models, based on different anthropometric tables, and validate Inverse Dynamics. BCoM trajectory in walking, running and skipping is well described by Inverse Dynamics models employing a whole body marker set, where the main body segments are considered for BCoM calculation. On the contrary, simplified estimation models employing few markers, such as just one marker on the trunk or the mean of the pelvis, poorly match Direct Dynamics trajectory. Same results come from the further analysis of muscular work, where whole body models better describe and match Direct Dynamics data. Some interesting observations emerged from these analyses: i) two anthropometric tables with quite different segments definition reach the same results; ii) whole body models of Inverse Dynamics well matched Direct Dynamics values, validating this methods, whereas poor models should not be employed anymore; iii) the difference between Inverse and Direct Dynamics in the same gait is almost speed independent highlighting a systematic error, and among gaits it shows the same trend; iv) race walking

BCoM trajectory cannot be described with any Inverse Dynamics models, therefore only ground reaction forces should be used for computation.

Skipping is the third paradigm of human locomotion. Differently from walking and running, it was only investigated on level ground, addressing the much expensive cost of transport as the reason for its under use in day life activity; conversely it was displayed by astronauts of Apollo missions on the Moon. In the second part of this thesis the mechanics and bioenergetics of skipping on gradient was investigated since Ed Mitchell during Apollo 14 mission explicitly said "That nice skipping gait that I liked was very easy to do going downhill". Gradient range was ±15%, the range of gradient presents on the Moon. On Earth skipping cost is higher than walking and running at all gradients and it decreases with speed, differently from the other gaits no minimum was found during downhill skipping, and it is impossible to skip at positive gradient steeper than 5% due to muscular demand and consequent fraction of metabolic power. When analysing mechanical parameters, the work done by muscles to move BCoM (W_{EXT}) and the work done to accelerate limbs with respect to BCoM (W_{INT}), skipping changes are similar to running with W_{EXT} decreasing with downhill gradient and increasing speed, whereas W_{INT} increases with speed. These results show that skipping on gradient can be performed on Earth only downhill due to the great metabolic demand. However, skipping cost of transport is always higher than walking and running at the same slopes. Based on these findings and astronauts' choices, we could expect that gravity plays an important role on skipping and locomotion cost of transport, which are analysed and discussed in the third part of this thesis. Low gravity locomotion can be studied on Earth with different methods, the gold standard is the parabolic flight, since with the adequate angle of the airplane parabola it is possible to obtain gravity levels ranging from hypo-gravity (including 0 g) to hyper-gravity. However the time available at low gravity simulation is only about 30 seconds, which is too short for metabolic measurements. The second most used method is based on the body weight suspension, where subjects are unloaded of the desired body weight by the suspension of the body via bungee cords or springs. We re-vamped the Margaria's low-gravity 'cavedium' with a treadmill and two bungee cords free to stretch until 16 m and let subjects walk, run and skip on a range of speed with Moon and Mars gravity, in order to study cost of transport and biomechanical parameters. Walking range of speed decreases with gravity and cost of transport decreases by 18% in hypo-gravity; higher decrements are shown in bouncing gaits, running and skipping. On the Moon their cost is the same and comparable with terrestrial walking values. Being on Earth was almost 40% higher than running, skipping shows the best decrease and a threefold gain in operative speed. This means that on the Moon human can skip three times faster than on Earth with the same metabolic power, whereas running gain is only twofold. Mechanically these cost changes can be explained by a reduction in pendulum-like recovery of energy in walking that needs a higher muscular work, whereas in skipping it is not shown. Moreover W_{EXT} is lower in low gravity and a greater reduction of W_{INT} in skipping compared with running can partially explain the major reduction in skipping cost. Another interesting aspect related to gait mechanics regards stability, and when the surface is slippery, as on the Moon due to regoliths, balance during support phase becomes an important issue. Skipping, compared to running, involves a shorter stance phase and also a double support, in which the trajectory of the flight can be adjusted. Moreover higher vertical forces on the ground and a greater angle at take off let the foot to be less slippery when pushing the body forward. Based on this biomechanical and bioenergetics analyses it can be concluded that human locomotion on hypo-gravity planets will be a bouncing gait and probably skipping could be preferred to running. Secondly the decrease of skipping cost up to walking values on Earth can explain the astronauts' choice of skipping during Apollo missions.

Preface

This thesis collects three projects elaborated during my doctorate, which aim to extend the knowledge about human bipedal locomotion from a mechanical and bioenergetics point of view. The first study was a methodological one aimed to compare two common methods for measuring the body centre of mass and to validate inverse dynamics, which is often used in laboratories, to direct dynamics. Moreover it was started to shade light about the body centre of mass trajectory of race walking, another topic developed during this doctorate but not presented in this thesis.

The second study regarded skipping, the third human gait, studying its featuring on gradient on Earth, this was important for completing the whole knowledge of human bipedal locomotion, without external aids, started by Margaria in this building almost eighty years ago.

The third study focused on human locomotion in simulated low gravity. In the sixties astronauts landed on Moon and often adopted skipping and hopping instead of walking, why did they do that? A mechanical and bioenergetics analysis of the three human gaits (walking, running, skipping) was performed on Martian and Lunar gravity level in the 'Low gravity cavaedium' in order to answer that question.

Something else was done during these three years (see Appendix A), but they are not presented in this thesis.

Introduction

Cost of transport in human bipedal locomotion on Earth

When humans perform a movement, their muscles contract performing the amount of work needed, this determined a parallel energy consumption, which can be measured with specific apparatus. Like cars consume fuel to cover a distance, e.g. one kilometre, also human locomotion consumes an amount of oxygen, which results in the energy cost to cover that kilometre.

The cost of transport (C, J/(kg m)) is defined as the net energy spent for moving a kilogram of body mass for a distance of one metre (Schmidt-Nielsen 1972):

$$C = \frac{\dot{V}O_2ss - \dot{V}O_2bas}{v}$$

where $\dot{V}O_2ss$ is the oxygen consumption during the exercise (ml/(kg min)), $\dot{V}O_2bas$ is the baseline metabolism (ml/(kg min)) and v is the progression speed (m/s). In order to convert $\dot{V}O_2$ in energy (J) the energetic equivalent of O_2 based on respiratory quotient value (RQ) is multiplied. With this parameter it is easy to compare individual with different size, moving at different speed and using different gaits.

Walking

Walking is the first learnt human bipedal gait and the most used during day life activities. Walking cost at increasing speed is characterised by a 'U-shape' function (Fig. 1), which shows a minimum (about 2 J/(kg m)) at intermediate speeds (1.11 – 1.38 m/s) and higher cost at slower and higher speeds (Margaria 1938). This 'optimal walking speed' is also the usually self-selected or spontaneous speed when walking. When moving uphill or downhill the range of speeds available differs causing a wider or narrower quadratic function but C always shows a minimum (Margaria 1938, Fig 2). This minimal cost increases monotonically with steeper gradient, whereas going downhill it reaches a minimum (about 1 J/(kg m)) at -10%, a further slope causes a concomitant increase of cost (Margaria 1938; Minetti et al. 1993, Fig 3). The reason for this 'U-shape' cost is still unknown, a first explanation for the minimum cost was related to Energy Recovery (Cavagna et al. 1976, see Mechanics section for further details): the minimum occurs where the 'pendulum-like' exchange were maximised and then the muscular energy needed to move was at its minimum. However when gradient walking was mechanically described (Minetti et al. 1993) data showed that the 'pendulum-like' exchange at gradient above +15% is totally impaired, but as shown by Margaria (1938) the minimum is always present at least until +40%. Hence even if Energy Recovery conclusion is fascinating it does not seem to be conclusive. On the other hand the reason for a minimum at -10% downhill can be ascribed to the partitioning of positive and negative external work and their different efficiency (Minetti et al. 1993).

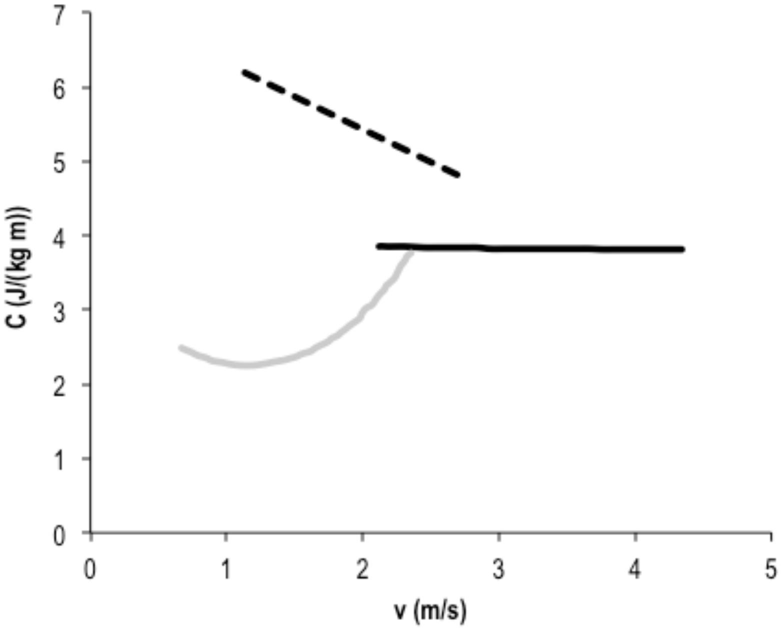

Figure 1. Cost of transport (J/(kg m)) at increasing speed (m/s) in the three gaits: walking (solid grey line), running (solid black line) and skipping (dashed black line). Modified from Minetti 1998a.

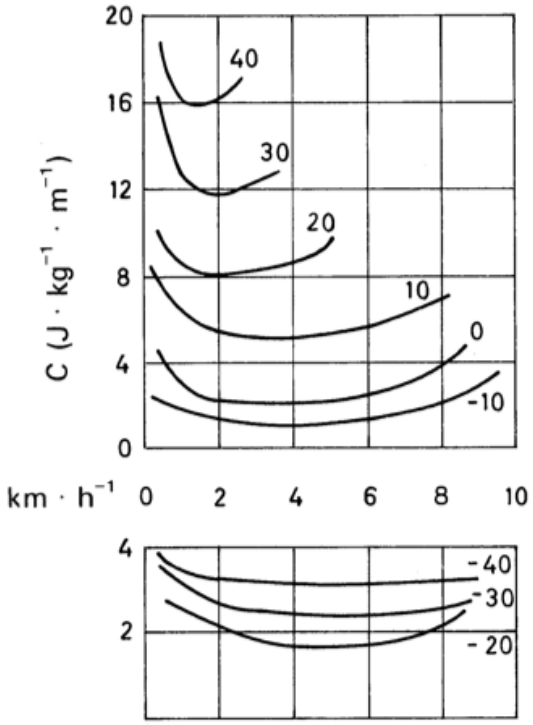

Figure 2. Walking cost of transport (J/(kg m)) at increasing speed (km/h) at different gradients (numbers near lines indicates slope percentage, negative numbers indicate downhill gradients). From Margaria 1938 in Di Prampero 1985.

Running

When humans decide to move faster, they usually increase their speed by changing gait, the spontaneous transition from walking to running occurs at 1.94 – 2.09 m/s (Thorstensson & Roberthson 1987). However this is an abrupt change rather than incremental, there is a speed range that is not used by people, since has been reported that the fastest walking speed is usually 1.94 m/s whereas the slowest running one is 2.36 m/s (Minetti et al. 2003). One of the determinants of this transition is metabolic (Saibene e Minetti 2003), in fact above 2.36 m/s walking cost is higher than running (Margaria 1938). Minetti and colleagues (1994) found that considering the cost per step instead of per meter, a parameter that could be better monitored by our nervous system, walking cost becomes greater than running, already at 2 m/s: at the spontaneous transition.

Running cost of transport across the speeds is constant, showing the speed-independency (Margaria et al. 1963, Fig. 1), differently from walking.

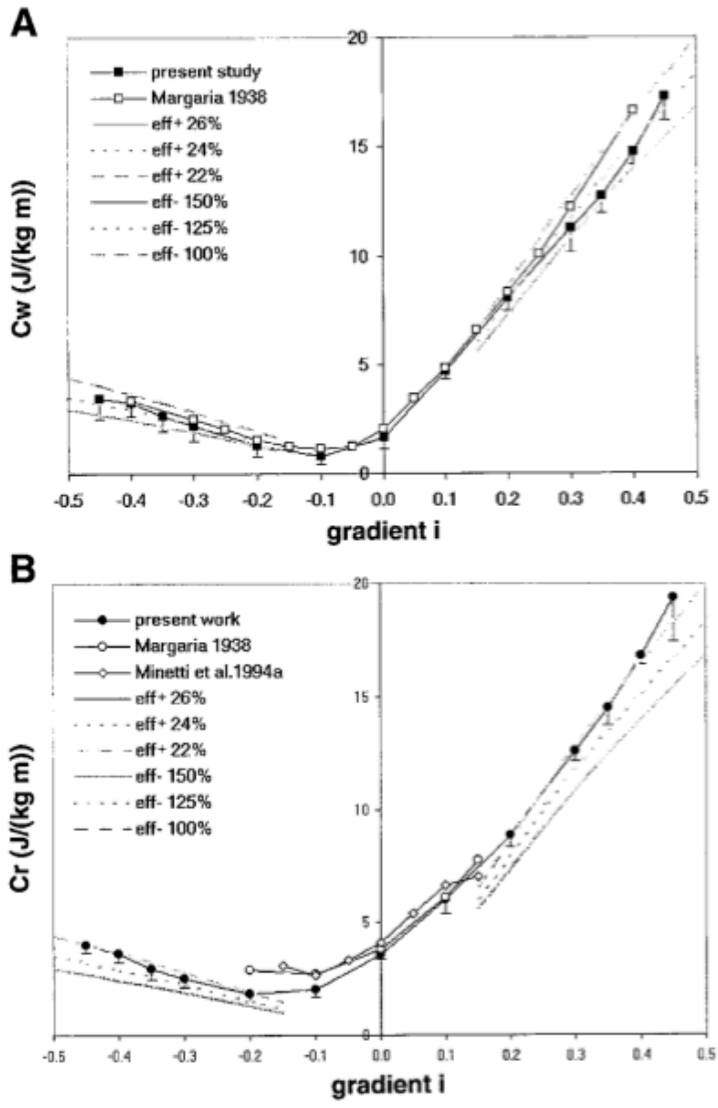

Figure 3. a) Walking cost of transport (J/(kg m)) at different gradient. At each gradient symbol indicates the minimum of walking cost. b) Running cost of transport (J/(kg m)) at different gradient (from Minetti et al. 2002).

This is true for aerobic running speed (2.22 – 5.56 m/s) performed on a treadmill, where the air resistance can be neglected (di Prampero 1986). When running uphill or downhill (± 45%) the speed independency is unchanged, and as in walking, with steeper uphill gradient the cost increase monotonically, whereas going downhill a minimum a -10% is found (Minetti et al. 2002). The reason(s) of this speed-independency is(are) still unknown even if the almost 'metabolic-free' elastic energy could play a role.

Skipping

Skipping is the third human gait, which resembles a pair of quadruped limbs while galloping, used by children for fun in short distance movements, and almost dismissed in adulthood; nevertheless adults use skipping when going down-stairs or cornering (Minetti 1998a). A possible reason of this disuse could be metabolic, when compared to walking and running (Fig. 1) skipping cost is significantly the highest with a possible decrement by increasing speed as in jumping kangaroos (Heglund et al. 1982) however range of speed is limited by the high power demanded. This high cost is possibly explained by muscular activity, which shows different and greater activation than in walking and running especially due to the leg asymmetry during mono-lateral skipping (Fiers et al 2013).

Mechanics of human bipedal locomotion on Earth

Since locomotion is a complex action, which involves the activation of many muscles, articular movements and stabilisation in order to move limbs, biomechanics described each gait with a 'paradigm', like a physical model that easily resembles and describes the gait analysing the trajectory of the body centre of mass (BCoM) and its energies time course. The most important parameter of a mechanical analysis is the total work (W_{TOT}, J/(kg m)) performed by muscles during locomotion. Adapting the König theorem to the locomotion system W_{TOT} can be obtained by the sum of external work (W_{EXT}, J/(kg m)), the work done to accelerate, decelerate and rise BCoM, and internal work (W_{INT}, J/(kg m)), the work done to accelerate and decelerate limbs respect to BCoM. W_{INT} has also an immeasurable part, which is composed by joint friction, cardiac work and muscular co-contraction (Cavagna e Kaneko 1977, Minetti 1998b). W_{EXT} is calculated analysing the time course of the BCoM total energy (Etot) during the stride, which is the sum of the potential energy (Pe) and 3D kinetic energies (progression, kx; medio-lateral, ky and vertical, kz)

$$\mathrm{E_{tot}} = \mathrm{mgh} + \frac{1}{2}\left(\mathrm{mv_x^2} + \mathrm{mv_y^2} + \mathrm{mv_z^2}\right)$$

where m is body mass (kg), g is acceleration of gravity (9.81 m/s), h is the vertical position (m) and v is the BCoM speed (m/s).

The sum of increments in Etot result in W_{EXT}, it should be called W_{EXT}^{+} since muscles are shortening performing positive work, whereas while stretching muscles perform negative work W_{EXT}^{-} which is calculated by the decrements of Etot. (Cavagna & Margaria 1966, Cavagna et al. 1976). The sum of increments of kinetic energy of the segment respect to BCoM and rotational energy of the limbs results in W_{INT} (Cavagna e Kaneko 1977, Minetti 1998b)

$$W_{INT} = \sum_{i=1}^{n} \left[\frac{1}{2} (m_i v_i^2) + \frac{1}{2} (m_i k_i^2 w_i^2) \right]$$

where i are the body segments, which number ultimately depends on the kinematic model chosen, v is the segment speed relative to BCoM (m/s), k is the segment radius of gyration (m) and w is the angular velocity of the segment (rad/s) (Fenn 1930).

However when stride frequency, duty factor and progression speed are known it is possible to calculate W_{INT} with an equation, which already takes in account the segments parameters with a constant q. For walking and running human q = 0.1 (Minetti 1998b)

$$W_{INT} = SF\ v \left[1 + \left(\frac{d}{1 - d} \right)^2 \right] q$$

where SF is stride frequency (Hz), v is mean progression speed (m/s), d is duty factor.

Cavagna and colleagues (1976) introduced a unique parameter for gaits that resemble a pendulum-like motion: Energy Recovery. When a pendulum oscillates, after the first push, it exchanges potential to kinetic energy and without friction it will oscillate forever. Energy Recovery (%) is the percentage of energy saved involving the pendulum-like motion.

$$\text{Energy Recovery} = \frac{(W_F + W_V) - W_{EXT}}{(W_F + W_V)}$$

Where W_F is the increment of kx energy, W_V is the increment of Pe.

Walking

Walking is a succession of steps where at least one foot is always in contact with the ground, and sometimes there is also a double contact phase, where both feet are simultaneously on the ground. The fraction of the stride period at which one foot is in contact to the ground is called duty factor (d) and in walking it is greater (or equal) than 0.5 (Alexander 1989).

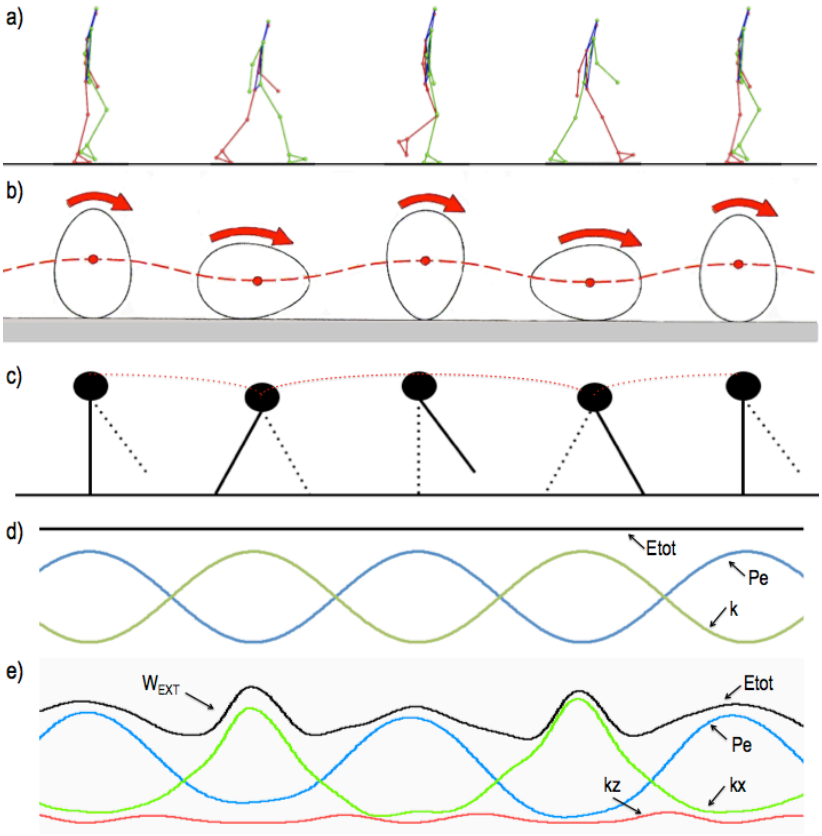

Figure 4. Walking. **a)** a stick diagram of a stride, with single and double support. **b)** the rolling egg, the first walking paradigm, where the vertical BCoM excursion is described. **c)** the inverted pendulum, BCoM during stance phase describes an arc of circumference like a pendulum. **d)** Theoretical potential, kinetic and total energy time courses during the perfect pendulum motion. **e)** energies time course during a human walking stride at 1.39 m/s obtain by a motion capture system, energies resemble the 'out of phase' pattern like in a pendulum-like motion, but show increase in total energy, the so called external work.

Walking has been classically described as a rolling egg or an inverted pendulum because BCoM exchange potential and kinetic energy out of phase, like in a pendulum (Margaria

1976, Fig. 4), with the highest position during single support and the lowest during double support. BCoM motion on sagittal plane could resemble an arc of circumference and assuming the stance leg as a rigid segment, it is an inverted pendulum, whereas the swinging leg acts like a straight pendulum. W_{EXT} and W_{INT} increase with speeds (Fig. 5), whereas Energy recovery showed a peak (Cavagna et al. 1976, Minetti 1998b). When walking on level and at constant speed, $W_{EXT}^{+} = W_{EXT}^{-}$, however, when moving on gradient the partitioning of positive and negative work change considerably (Fig. 6) and above +15% the external work is totally W_{EXT}^{+}. BCoM trajectory increases monotonically walking uphill, and there is a concomitant decrement of progression because of the steeper gradient. In this condition, most of the work that muscles perform is needed to raise BCoM (W_F) and increase Pe. This unbalance between Pe and ke, causes a reduction of Energy Recovery and the impairment of pendulum-like motion, with a higher demand of muscular power and higher cost of transport. Walking downhill conversely shows a decrease in BCoM trajectory and the partitioning of external work reaches almost totally W_{EXT}^{-} at steeper gradient, with a concomitant impairment of Energy Recovery. When walking at the same speed, gradient does not seem to alter W_{INT}.

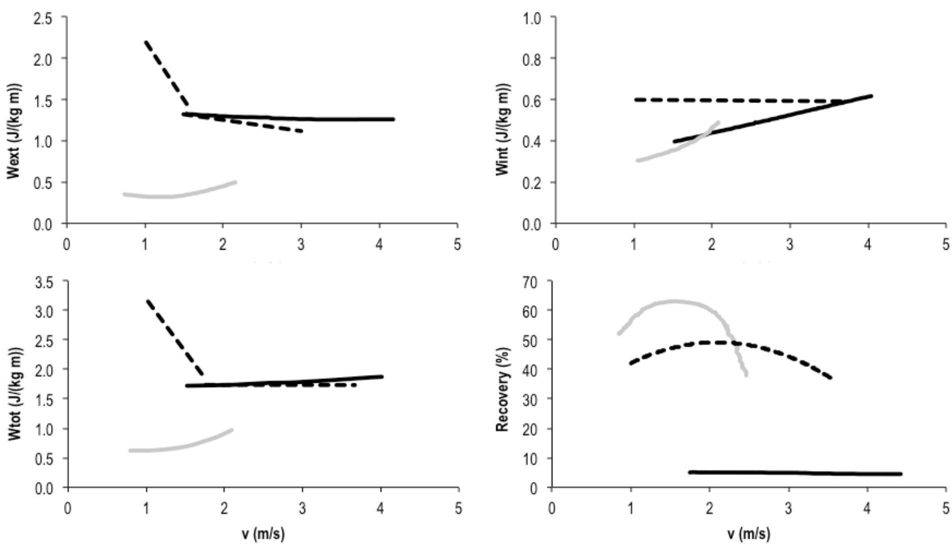

Figure 5. Top left, mechanical external work (J/(kg m)). Top right, mechanical internal work (J/(kg m)). Bottom left total mechanical work (J/(kg m)) and bottom right Energy Recovery (%) as a function of speed (m/s) in the three gaits: walking (solid grey line), running (solid black line) and skipping (dashed black line). Modified from Minetti 1998a.

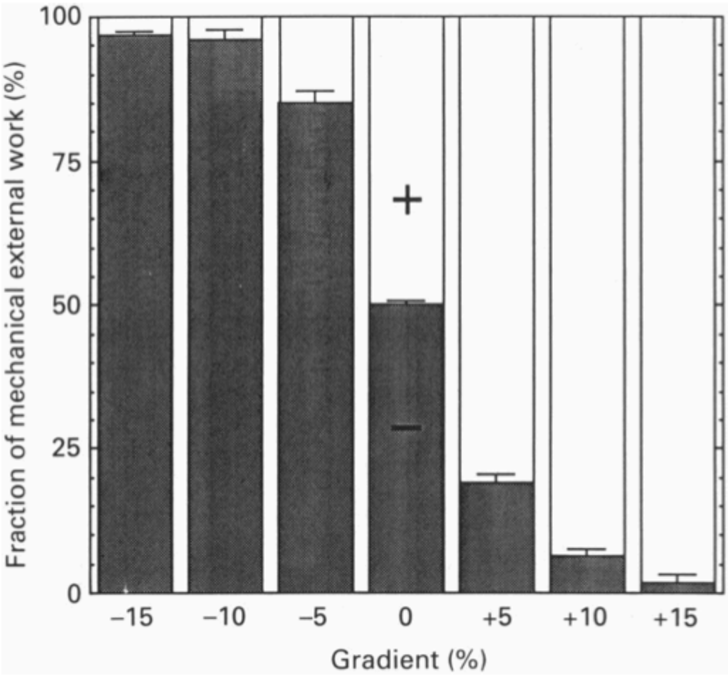

Figure 6. Partitioning of mechanical external work (%) at different gradient in walking. White column W_{EXT}^{+}, black column W_{EXT}^{-} (from Minetti et al. 1993).

Running

Running is a progression of steps with an aerial phase between each ground contact, and duty factor is smaller than 0.5.

Running has been classically described as a bouncing ball (Margaria 1976) and later refined as a spring mass model (Blickhan 1989) where the body is modelled as a point mass on the top of a spring, which resembles lower limb action. Both models well describe the peculiarity of running: Pe and ke are in phase, no pendulum exchange, and at the contact to the ground part of the total energy is stored on the stretching elastic elements, mainly Achilles tendon and plantar arch of the foot (Ker et al. 1987), and is given back during push off, reducing muscular work (Fig. 7).

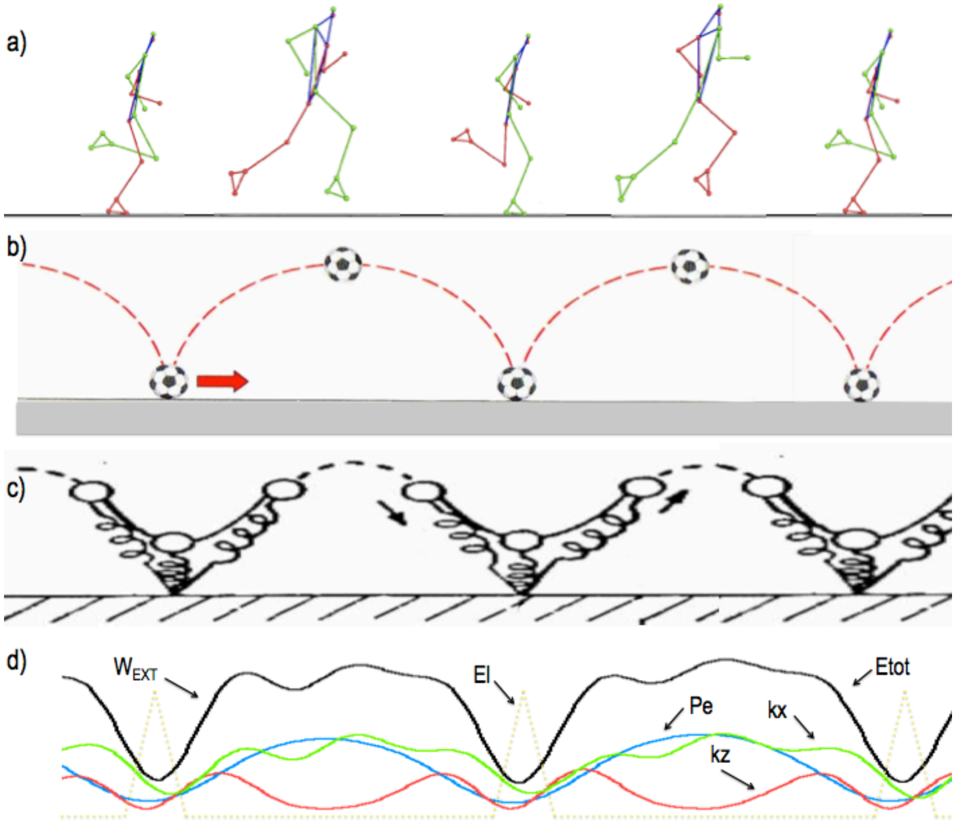

Figure 7. Running. **a)** a stick diagram of a stride, with single support and flight phase. **b)** the bouncing ball, the first running paradigm, where the vertical BCoM excursion is described. **c)** the spring mass model, BCoM during stance phase compresses the spring of the lower limb. **d)** energies time course during the running stride at 4.44 m/s obtain by a motion capture system, potential and kinetics energies are 'in phase' and total energy is the sum of them, however during the first half of stance part of the total energy is stored in elastic element rising elastic energy, which is released in the push phase.

The presence of this elastic energy (El) is crucial for reaching high progression speed, when muscle works almost isometrically (Roberts et al. 1997), and for helping muscles in order to move BCoM. This synergic action of elastic energy ultimately lowers cost of transport, however the energy supply raises problems on the validity of W_{EXT} calculation. In this case the synergic action of muscles and elastic elements lifts and accelerates BCoM, hence the calculated W_{EXT} is not the result of muscular contraction. Speed influences all biomechanical parameters: W_{EXT}, W_{INT} and SF increase with speed, vice versa duty decreases (Cavagna & Kaneko 1977, Fig. 5). As in walking when moving on gradient the partitioning of W_{EXT}^{+} and W_{EXT}^{-} changes, uphill W_{EXT}^{+} becomes predominant, but different to walking there is a higher fraction of W_{EXT}^{-} probably because the bounce maintains a BCoM downward trajectory before heel strike. Conversely downhill W_{EXT}^{-} is predominant with residual W_{EXT}^{+} probably due to a minimal upward BCoM trajectory after push off. W_{INT} increases with positive gradients, mainly a SF effect, but is unchanged with negative gradients, excluding its contributes to the minimum of running cost at -10% (Minetti et al 1994).

Skipping

Skipping involves, within a stride single, both double contact and flight phase. It could be mono- or bi-lateral: mono-lateral displays always the same leading (fore) and trailing (rear) foot and is an asymmetrical gait, which is called 'right' or 'left' from the leading foot. The footfall sequence for mono-lateral skipping is trailing (single support) -leading (double support) leading (single support) and flight. Bi-lateral skipping changes the leading and trailing foot at each stride, during swing phase the rear leg goes ahead becoming the fore in the subsequent stride (Minetti 1998, Fig. 8).

Skipping paradigm was described in 1998, it merges the pendulum-like model during double support, whereas the spring mass model in the single support phases and during flight phase the ballistic motion (Minetti 1998). These two features shared with walking and running allow skipping to use Energy Recovery, with values closer to walking, and elastic energy. W_{EXT} values are almost speed independent as in running, moreover W_{INT} and SF are also speed independent differently from both walking and running (Fig. 5).

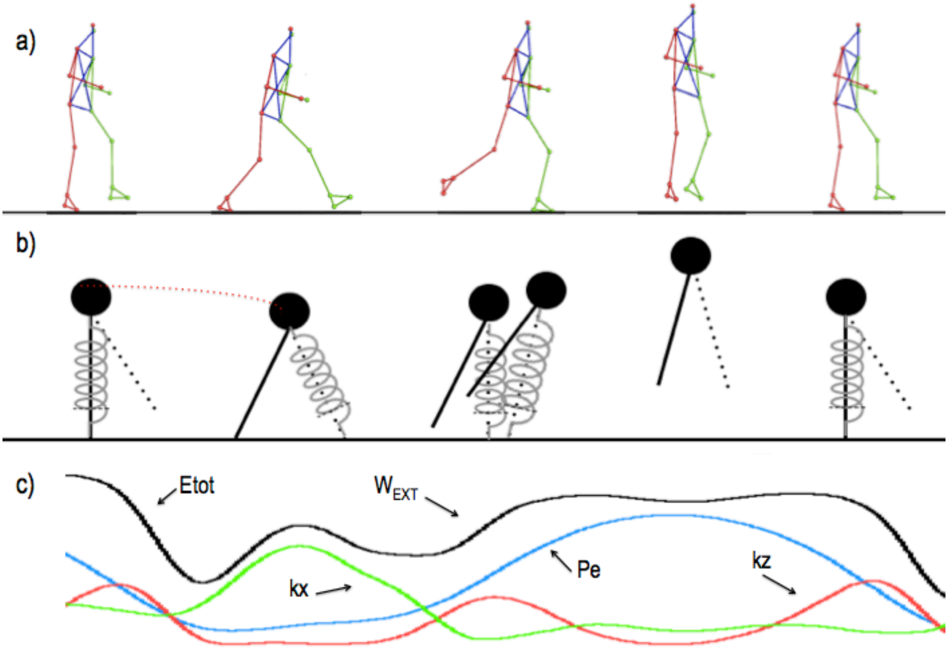

Figure 8. Skipping. **a)** a stick diagram of a stride, with single, double support and flight phase. **b)** the inverted pendulum with a spring mass model is the skipping paradigm, during first foot stance BCoM compresses the spring and then describes and arc of circumference during double support. In the second foot stance there is the compression of the second spring, which allows flight phase. **c)** energies time course during a skipping stride at 3.06 m/s obtain by a motion capture system, potential and kinetics energies are 'out of phase' during the support.

Efficiency

Efficiency is defined as the ratio of total mechanical work and energy consumption. Higher is this ratio, less is the energy lost by the system.

$$Eff = \frac{W_{TOT}}{C}$$

In human legged locomotion the maximal efficiency should be the muscular efficiency, which maximum is 0.25 (Woledge et al. 1985). However, the presence of elastic elements can increase this value and when efficiency is greater than 0.25 it should be called 'apparent efficiency'.

Walking efficiency is close to the muscular value and shows a specular U shape compared to cost, with peak at minimum cost; running efficiency vice versa increases as a function of speed and it is much greater than 0.25, this is mainly determined by the tendons and elastic elements work that 'helps' muscles reducing the cost of transport and also perform work that enhances W_{TOT} value. Elastic elements action varies efficiency value by inflating numerator. Skipping also uses elastic energy, and the efficiency is something higher than muscular (Fig. 9).

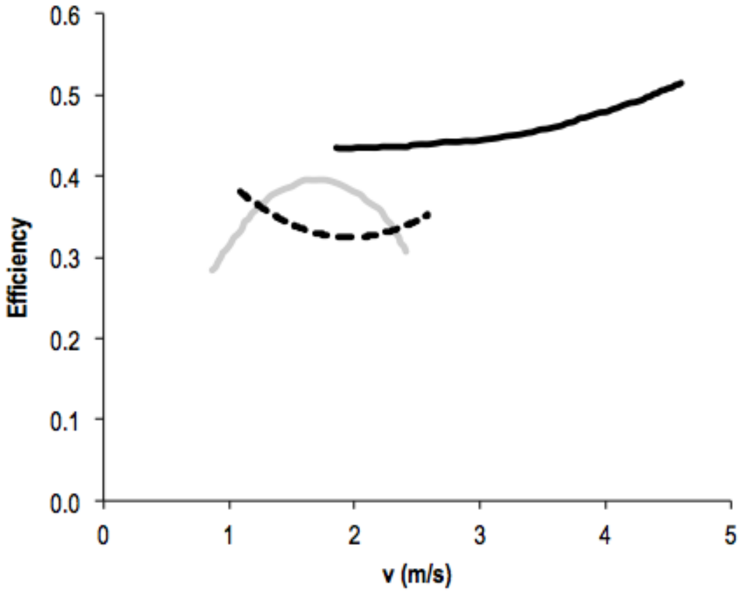

Figure 9. Efficiency as a function of speed (m/s) in the three gaits: walking (solid grey line), running (solid black line) and skipping (dashed black line). Modified from Minetti 1998a.

Bipedal human locomotion in low gravity

Studies on human response to hypo-gravity started years before Lunar landing and were addressing many physiological aspects: circulation, respiration, heat, dehydration, … and also locomotion. The first investigations analysed comes from NASA technical reports, but we can expect that also URSS space program elaborated and tested cosmonauts without publishing their results. In the sixties four methods were used to simulate and study human locomotion in low gravity: water immersion, inclined plane locomotion, body weight support and parabolic flight.

Water immersion consists in placing subjects insight a pool with weight on the pelvis in order to maintain them underwater in a stable position, they breath via a scuba and locomote on an underwater treadmill (Fig. 10b). In this way all the body has the same gravity, but water density is almost 800 times greater and 60 times more viscous than air, thus movements are more expensive and secondarily maximal speed are reduced due to balance problems (Spady 1970).

Inclined plane locomotion was a NASA patent (Fig. 10d), subject was suspended by cables, fixed on the trunk and each limb, and moved on an inclined walkway, the grade of inclination changed in order to obtained the desired hypo gravity. This apparatus allows the whole body to be at the same gravity and locomotion was almost normal. However walkway length limited data acquisition and collecting metabolic data was almost impossible (Hewes et al. 1966).

Body weight support system unloads body weight via springs, rubber bands or counterbalance weight (Fig. 10c). Usually subjects wear a harness, which is connected to the cable (Worth & Prescott 1966, Cavagna et al. 1972). The major limitation of the system concerns the application of unloaded force to the trunk, with limbs free to move at Earth gravity, however a recent study on walk-run transition on parabolic flight found similar results to body weight support system (De Witt et al. 2014), a kind of validation of the system.

Parabolic flight obtains the desired gravity levels during the top of the parabola due to the centrifugal force (Hewes & Spady 1964, Fig. 10a). It is considered the gold standard because everything inside the airplane cabin feels the obtained gravity (including 0g condition). Almost every gait could be studied mechanically (Cavagna et al. 2000), whereas the short time of the parabola (at top 25 s in low gravity conditions) is too short for acquisition of metabolic data since subjects cannot reach a steady state of oxygen consumption.

Walking and running mechanics in hypo gravity was investigated for the first time by Margaria & Cavagna (1964) theoretically, extending their earlier studies on walking and running on Earth (Cavagna et al. 1963, 1964). Looking at the potential, kinetics and total energies time courses they concluded that walking on the Moon would be impaired, since potential energy is reduced due to 0.16 g, with a maximal walking speed of only 0.28 m/s. Maximal running speed would also be decreased to only 3.61 m/s, a confortable running speed for a master athlete during marathon on Earth. In this case the vertical component of force is affected by low gravity, and the reduction causes a decrease in the angle between vertical and forward forces, when this value becomes smaller than 45° the body falls down since foot is skidding, with hard surface the lowest angles allows to run up to 3.61 m/s. In order to overcome these problems Margaria and Cavagna proposed a 'third' possible gait, a progression of jumps: hopping. In hopping, the take off angle is close to 90°, the base of support is provided by two feet, being greater than in running and skidding could be avoided. Moreover, hopping uses a lower step frequency, which could be less metabolic expensive (Margaria & Cavagna 1964, Margaria et al. 1967).

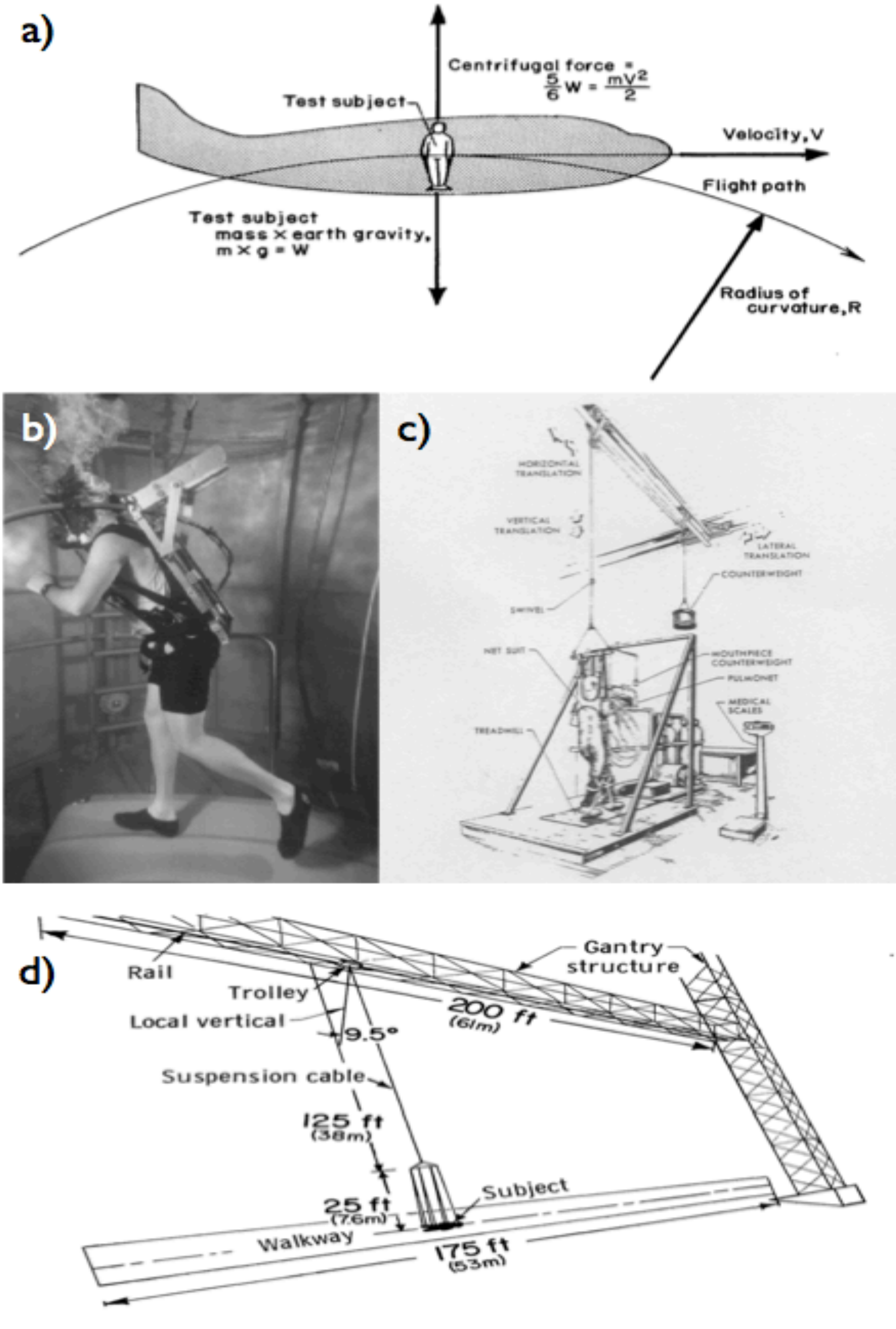

Figure 10. Different hypo-gravity simulator: **a)** parabolic flight (from Hewes & Spady 1964); **b)** water immersion (from Spady 1970); **c)** body weight support system (from Worth & Prescott 1966) and **d)** inclined plane locomotion (from Hewes et al. 1966).

The most comprehensive investigation in walking mechanics at different gravity levels was performed by Cavagna and co-workers (1998, 2000) during parabolic flights on the whole range of walking speeds. Their parabolas investigated walking on Mars (0.4 g) and at 1.5 g by means of a dynamometric corridor fixed on the plane. Walking speeds range is affected by gravity (Fig. 11): on Mars maximal walking speed is decreased, on 1.5 g is increased. W_{EXT} also changes with gravity, low gravity walking needs less W_{EXT}, whereas hyper gravity needs more W_{EXT} this is addressed to both differences in W_F and W_V. The Energy Recovery shifts to slower speed on Mars also decreasing its maximal value. Griffin et al. (1999) found similar W_{EXT} trend by analysing walking on a range of gravities (0.25 – 1 g) using a body weight support system.

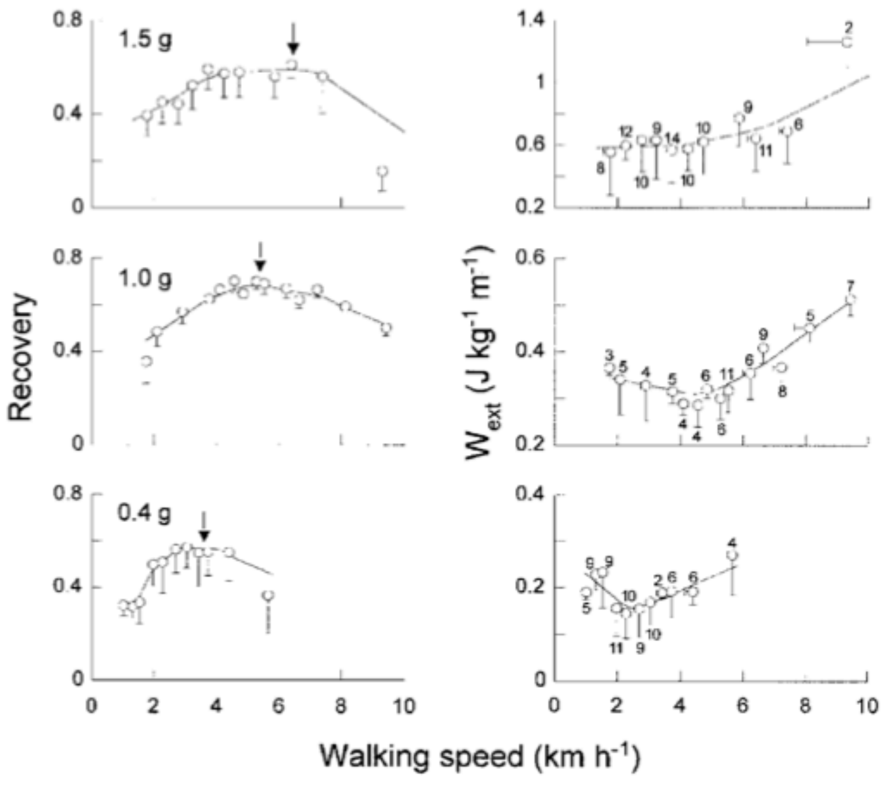

Figure 11. Walking energy recovery (left) and mechanical external work (right, J/(kg m)) as a function of speed (km/h) in three different gravity conditions (1.5 g top, 1 g middle and 0.4 g bottom panel) (from Cavagna et al. 2000).

The ‘optimal speed’, where there is maximal Energy Recovery, walking speeds range, and consequently the walk-run transition (Ivanenko et al. 2011) are reduced with gravity (Cavagna et al 2000). These variations can be predicted by a simple relationship: the Froude number. The Froude number (Fr, Alexander 1989) is used in animal-legged locomotion to compare the speed of different size body (Alexander 1989) and/or the same body on different gravity levels (Minetti 2001a,b). Fr is based on the dynamic similarity theory (Alexander 1989): subjects of different size or in different gravity environments move similarly with the same Fr.

$$Fr = \frac{v^2}{g\, l}$$

where v is the progression speed (m/s), g is the acceleration due to gravity (m/s^2) and l is a characteristic length, usually leg length (m). Fr is a dimensionless number since the same units appear at numerator and denominator. When using Fr for comparing different size animals or in different gravity environments three values were found to be invariant and important: Fr = 1, is the dimensionless speed limit of walking. As a matter of facts Fr is the ratio between centrifugal and centripetal force, hence when the ratio is greater than 1 the body is no more in contact to the ground, a flight occurs, and the gait can not be consider walking anymore. Fr = 0.5 has been shown to be the spontaneous transition speed between walking and running. Fr = 0.25 is the dimensionless speed corresponding to the walking ‘optimal speed’. When moving at the same Fr in different gravity environments the equation can be rewritten as:

$$v_1 = v_2 \sqrt{\frac{g_1}{g_2}}$$

where v_1 is the progression speed (m/s) and g_1 is the gravity (m/s^2) of planet 1 and v_2 and g_2 speed and gravity of planet 2. The absolute speeds (m/s) are different, but the dimensionless (Fr) is the same. Figure 12 shows how Froude’s prediction well interpolated experimental data of walking at different gravity level present in literature (Minetti 2001a,b).

Mechanics of running in hypogravity was investigated only in one study focusing on leg stiffness rather then mechanical work with a body suspension device (He et al. 1991).

Across the gravities (0.2 – 1 g) they found that the spring stiffness of the leg is almost invariant, as occurs changing speeds, highlighting the same behaviour of human musculo-skeletal system in different speed/gravity conditions. Conversely when running in hyper-gravity (1.3 g) W_{EXT} increases 1.3 times compared to 1 g, this linear increase is obtain with a parallel increment of both W_V and W_F. If the increase in W_V could be expected on the basis of a higher g level, W_F increase is less obvious, nevertheless f the angle between vertical and progression forces remains the same, both works increases proportionally, occurring at 1.3 g, showing that at any given speed the average direction of the push is independent of gravity (Cavagna et al. 2005). In hyper-gravity leg stiffness remains almost the same and the increase in power is mainly due to an increase in step frequency and a reduction of aerial time (Cavagna et al. 2005).

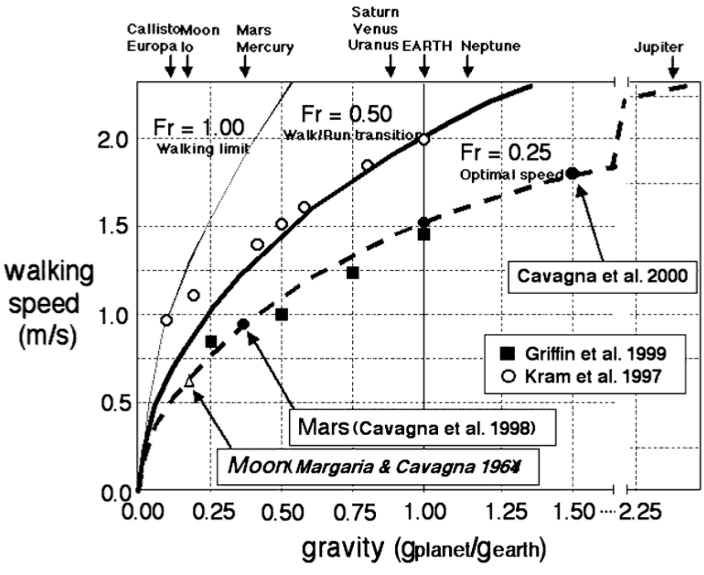

Figure 12. Walking speed (m/s) as a function of gravity. Iso-Froude lines for optimal speed (Fr=0.25), transition speed (Fr=0.5) and maximal walking speed (Fr=1) are presented and well fit experimental data (from Minetti 2001b).

Bioenergetics measurements of hypo-gravity locomotion can be obtained only on Earth via a body suspension system, which could involve some systematic errors due to the mechanics of apparatus. Probably the first is the cost of transport overestimation due to limbs weight. In fact limbs are free to move at Earth g and muscles have to move their weight, which should be lighter (BW = mg) in hypo-gravity condition. This error is common to every experimental setting and since parabolic flight duration cannot reach the steady state time, and now we are not be able to collect data on human gait in real hypo-gravity conditions, this is the only method to study bioenergetics in different gravity levels.

The first study in 1962 exploited the limit of body suspension that allows human walking. Lomonaco et al. (1962) had subjects walking at 0.05 g and found that walking at 1 m/s was kinematically quite difficult, because flight phase occurred, and walking was metabolically 34% more expensive than on Earth. These results were probably biased by the impressive unload imposed to the subjects. Wortz and Prescott (1966) simulated three hypo-gravity (0.25, 0.17, Moon value, and 0.12 g) subjects walked at two speeds (0.89 and 1.78 m/s) and in both occasion the energy cost in hypo-gravity was significantly lower than on Earth (-30% at 0.89 m/s and -55% at 1.78 m/s), but it was not different among gravity level. Farley and McMahon (1992) compared walking at 0.5 and 1 g on a range of speed (Fig. 13a) and introduced also running, moreover at one walking (1 m/s) and running (3 m/s) speed they tested different hypo-gravity levels (Fig. 13b) with a body weight suspension system. Their results show that walking and running at 0.5 g is less expensive than at 1 g and that running cost is the same than walking (Fig. 13a). When compared on a wider range of gravities, running cost decrement is nearly proportional to hypo-gravity (-72% cost when running at 0.25 g, i.e. a 75% reduction) and greater than walking (-33% cost when walking at 0.25 g, i.e. a 75% reduction), and at 0.25 g running is more economical than walking, highlighting that walking is not be the cheapest way to move in low gravity conditions. However these percentage reductions have been mitigated in two successive studies using similar body weight suspension systems, Grabowski et al. (2005) found in walking a reduction of only 21%, instead of 33% at 0.25 g and 11% instead of 25% at 0.5 g. In running Teunissen et al. (2007) did not find a proportional cost and gravity reduction, at 0.5 g cost reduction was 60% and at 0.25 g the reduction was 43%. They concluded that these differences were introduced by the suspension system, in Farley and McMahon (1992) setting the cable connecting the harness to the top pulley over the subject's head was (too) short and applied an aiding horizontal force that probably helped subjects during progression. This aid ultimately affected cost of transport by decreasing it (Teunissen et al 2007).

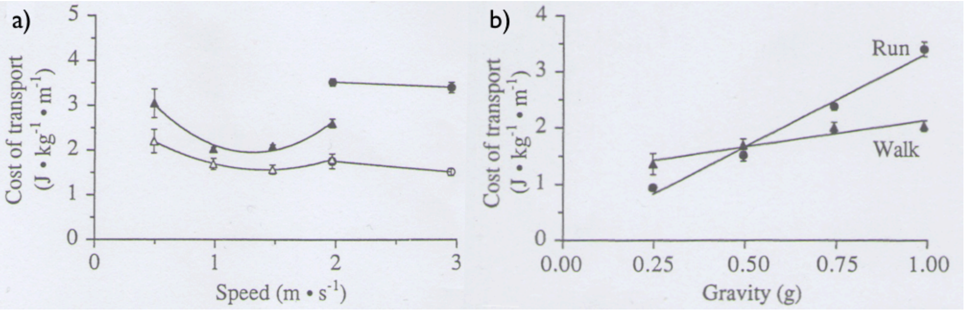

Figure 13. a) walking (triangles) and running (circles) cost of transport (J/(kg m)) at increasing speed (m/s) in 1 g, filled symbols, and 0.5 g conditions, empty symbols. **b)** walking (triangles, speed 1 m/s) and running (circles, speed 3 m/s) cost of transport (J/(kg m)) at different gravities level (g) (form Farley and McMahon 1992).

All the aforementioned studies refer to unsuited human locomotion, since it is very difficult to obtain a space suit for experiments and most of the nowadays space suit are designed for space shuttle flight and/or extra vehicular activities on deep space, and not for locomotion.

From NASA pilot studies it is reported that locomotion with a space suit is more expensive mainly because the experiments in 1 g conditions are affected by space suit weight, which should be supported by its own pressure in hypo-gravity conditions. This causes a high metabolic rate imposed by the space suit, which ultimately limited also the operative subject's capabilities. However, it seems that pressure space suit can act as springs at joint level helping human locomotion, especially running, probably decreasing cost in real hypo-gravity conditions (Carr & Newman 2007a,b), similarly to octapods.

Nothing is known about skipping cost in hypo-gravity, even if it was chosen more times during Apollo missions (Fig. 14). On Earth, Minetti (1998a) showed some mechanical advantages compared with running that could be more useful on slippery Lunar surface increasing balance and progression speed: higher vertical ground reaction force, longer flight time and greater support area during contact. Secondarily, skipping on Earth is really expansive and never used, why astronauts adopted it on the Moon?

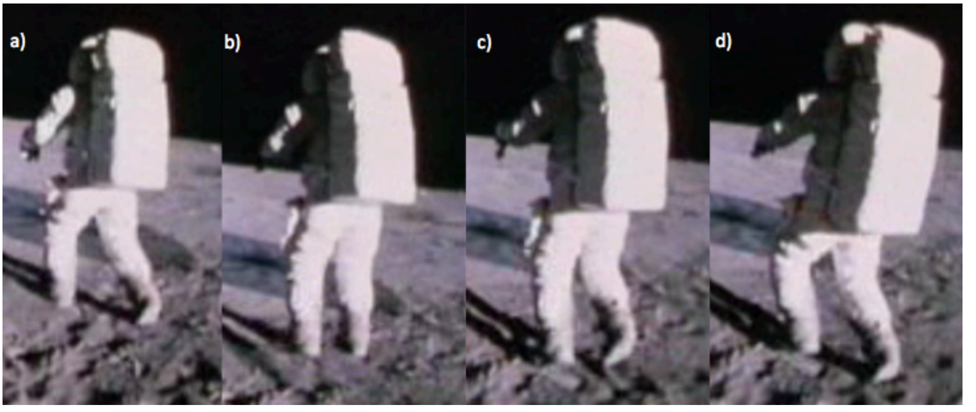

Figure 14. Buzz Aldrin skipping on the Moon. He moves right to left: in **d** double support, **c** single support, **b** flight and **a** double support of a mono-lateral left skipping (from NASA movie).

First study

This study was carried out in the laboratory of the "Unité de Physiologie et Biomécanique de la Locomotion" of the Univerisité Catholique de Louvain (Louvain-La-Neuve, Belgium) thanks to the courtesy, availability and knowledge of Professor Norman C Heglund and his staff.

Inverse and Direct Dynamics: Two methods for describing the same body centre of mass trajectory and related biomechanical parameters.

Introduction

Human body motion can be described as the trajectory of the body centre of mass (BCoM), which can be computed with two different methods: i) by double integration of ground reaction forces measured by force platforms or transducers, based on Newton's Second Law: Direct Dynamics (Cavagna 1975) and ii) by the weighted mean of segments centre of mass, which is computed by an optoelectronic system: Inverse Dynamics (Fenn 1930b). From the BCoM trajectory and time courses of related energies it is possible to obtain the mechanical work performed by muscles during the locomotion (W_{EXT}, Cavagna et al. 1963, Cavagna et al. 1976).

Direct Dynamics is considered the "gold standard" since it describes BCoM including also visceral mass and is not depending on anthropometric tables. However it assumes that subject moves on the platforms at constant speed with a perfect stride cycle: initial and final BCoM vertical and medio-lateral position are the same, usually this does not happen then integration constants are included. When platforms are on the floor, into a laboratory or a walkway, usually they allow capturing only a limited number of strides and many trials are needed in order to obtain reliable results. Recently, the increased number of instrumented or force mounted treadmills tried to ride over this problem, although a new filtering issue has risen due to treadmill vibration (Kram et al 1998, Belli et al. 2001).

Inverse Dynamics, conversely, acquires data from a subject moving on treadmill, hence there is an adequate stride number and speed is constant. Segment parameters are linked to anthropometric table, and different tables could be employed, increasing discrepancy.

Moreover markers placement and skin motion could add systematic errors on calculation (Chiari et al. 2005, Leardini et al 2005). Inverse Dynamics assumption regards segments, which are modelled as rigid bodies, hence cannot vary their length, and visceral mass in the trunk and soft tissue at joint level are not considered (Cazzola et al 2014).

In literature both methods are used interchangeably even if a complete validation of Inverse Dynamics is missing. The only few comparisons, mostly in the vertical axis have been performed only at one speed during walking (Whittle 1997, Thirunarayan et al. 1996, Eames et al. 1999, Gard et al. 2004, Gutierrez-Farewik et al. 2006) and on a range of speed in running (Gullstrand et al. 2009). The aim of this study was to compare Direct and Inverse Dynamics in 3D in four human gaits (walking, running, skipping, race walking) on a wide range of speed. Moreover since in literature many marker sets are present we tested five of them with Direct Dynamics in order to understand if they can be used interchangeably.

Materials and Methods

Subject and Protocol

One subject (1.78 m height, 63 kg body mass) skilled with treadmill locomotion and trained to all gaits and speeds performed the experiment. The study was approved by the University Ethics Committee and the subject signed an informed consent.

The protocol included walking, running, race walking and skipping at increasing speed: Walking speeds range was 0.278 – 1.944 m/s with 0.278 m/s increment; running 2.222 – 5.556 m/s, with 0.278 m/s increment; race walking 2.222 – 4.167 m/s, with 0.278 m/s increment, Skipping Mono- and Bi-lateral 0.833 – 3.056 m/s, with 0.556 m/s increment. At each speed data were collected for one minute after the subject reached a steady locomotion and three minutes of rest elapsed between each acquisition.

Data Acquisition

Kinematics data were acquired by mean of a 8-camera Vicon system (6 MX 1.3, 2 T20-S, Oxford Metrics, UK) at a sampling rate of 300 Hz. A Mercury LT med treadmill (HP Cosmos, Germany) with a 1.5 m long and 0.5 m wide belt, equipped with four 3D strain-gauge force traducers (Dierick et al. 2004) was used to collect ground reaction forces at

900 Hz. Analyses were performed stride by stride, and a threshold on left heel marker vertical position was used to detect heel strike.

Data Analysis

Five different kinematic models (Inverse Dynamics) for BCoM calculation were used: i) a single marker placed on the spinal process of 7th vertebra (C7), ii) the mean of anterior and posterior superior iliac spines obtained by the position of four markers placed on the anterior and posterior iliac spines (Spinae) (Whittle 1997), iii) a 11-segment body: trunk, arms, forearms with hands, thighs, shanks and feet modelled with 18 markers: bilaterally (right and left) occipital lobe, shoulder, elbow, great trochanter, knee, lateral malleolus, ~~heel~~, 5th metatarsal, based on Dempster tables (18mkr) (Minetti et al. 1993), iv) a 14-segment body: head, upper middle and lower trunk, arms, forearms with hands, thighs, shanks and feet modelled with 22 markers: bilaterally (right and left) occipital lobe, shoulder centre of rotation, elbow centre of rotation, great trochanter, knee centre of rotation, lateral malleolus, calcaneous, toe, middle point of two markers placed laterally (right and left) to omphalion, middle point of two markers placed laterally (right and left) to xyphion based on De Leva tables (De Leva) (De Leva 1996), v) a 14-segment body: head, trunk, arms, forearms, hands, thighs, shanks and feet modelled with 36 markers: spinous process of C7 and T10 vertebrae, sternum, jugular notch, and bilaterally (right and left) on temple and a marker symmetrical on the back of the head, acromion, elbow centre of rotation, radius and ulnae epicondyles, dorsum of hand, anterior and posterior iliac spines, lateral epicondyles of knee, lateral malleolus, calcaneous, toe, lower lateral surface of the thigh, lateral surface of the arm, as described in Vicon Plug-in-Gait model (PlugInGait) (Nexus 1.81 version, Oxford Metrics UK).

Markers position of C7, Spinae, 18mkr and De Leva were filtered 'zero-lag' with a second order Butterworth low pass filter with a cut-off frequency detected by a residual analysis on each marker coordinate (Winter 1979). Conversely PlugInGait was already filtered in the Nexus routine.

As for Direct Dynamics, BCoM from ground reaction forces was computed by double integration according to Cavagna (1975) and integration constants were calculated as described in Saibene & Minetti (2003), then down sampled in order to match inverse dynamics length (GRF).

Based on the spectral analysis of the ground reaction forces in three axes a filter was developed in order to preserve the signal for a Fourier analysis with 6 harmonics (Minetti et al. 2011). The spectral analysis, showed noise frequencies at 39, 47, 110 and 114 Hz, which were speed and gait independent, then ground reaction forces in three axes were filtered by a forward and reverse low pass filter 4th order Butterworth with a cut off frequency of 30 Hz. In order to delete an additional component at 24 Hz in the medio-lateral force, a 3rd order Bassel notch filter set on 24 Hz with a 'stopband attenuation' of 60 dB was used (Fig. 1).

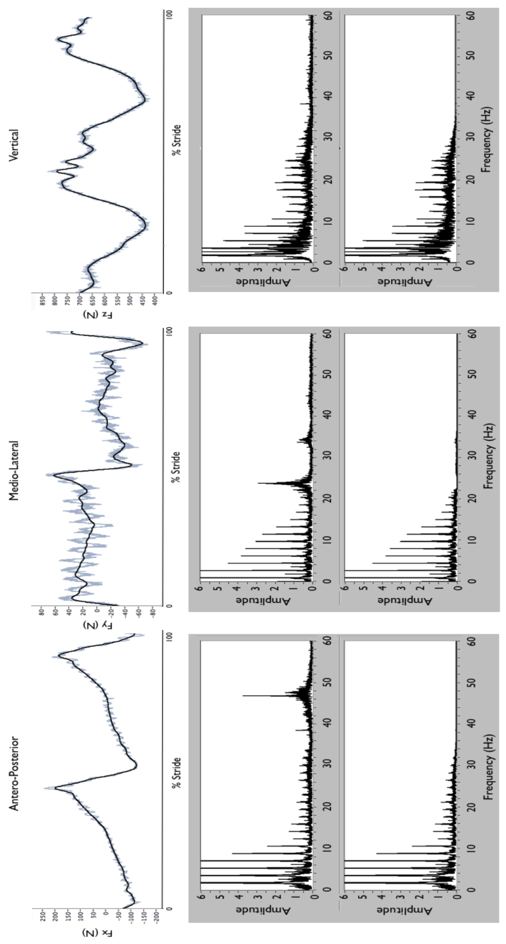

Figure 1. Upper Panel: ground reaction forces (GRF) in the three planes of motion during one walking stride at 1.39 m/s. Grey line original signal, black line filtered signal.
Lower panel: power spectrum of each GRF before (upper part) and after (lower part) the filtering process.

The obtained stride BCoM trajectories with the same sample size were closed in a loop (Minetti et al. 2011) and a point-by-point 3D root mean square (3D RMS, m) was computed between GRF and each Inverse Dynamics model. In order to avoid any possible phase shift introduced by filtering, an automatic 3D routine shifted Inverse Dynamics closed loop in order to find the minimal 3D RMS. The external mechanical work (W_{EXT}, J/(kg m)), the work done to accelerate and raise BCoM, was calculated for each model by summing the increment of total energy time course (Cavagna & Margaria 1966). Energy Recovery, the ability of a pendulum-like motion to exchange potential energy into progression kinetic energy was calculated by the time course of potential and kinetic energies during the stride (Cavagna et al. 1976). Mechanical internal work (W_{INT}, J/(kg m)) the work done to accelerate body segments respect to BCoM (Cavagna & Kaneko 1977, Minetti 1998) was calculated using the body segments of 18mkr with respect to BCoM calculated from GRF and with respect to BCoM obtained from 18mkr in order to investigate possible differences in the two computational methods.

Results

The 3D RMS (m) between GRF and each Inverse Dynamics model for every gait at increasing speeds are presented in figure 2. C7 and Spinae showed the greatest distances from GRF, whereas 18mkr and De Leva well matched all gaits, with the exception of race walking for 18mkr. PlugInGait was in accordance to Direct Dynamics when modeling running, quite far in the other gaits.

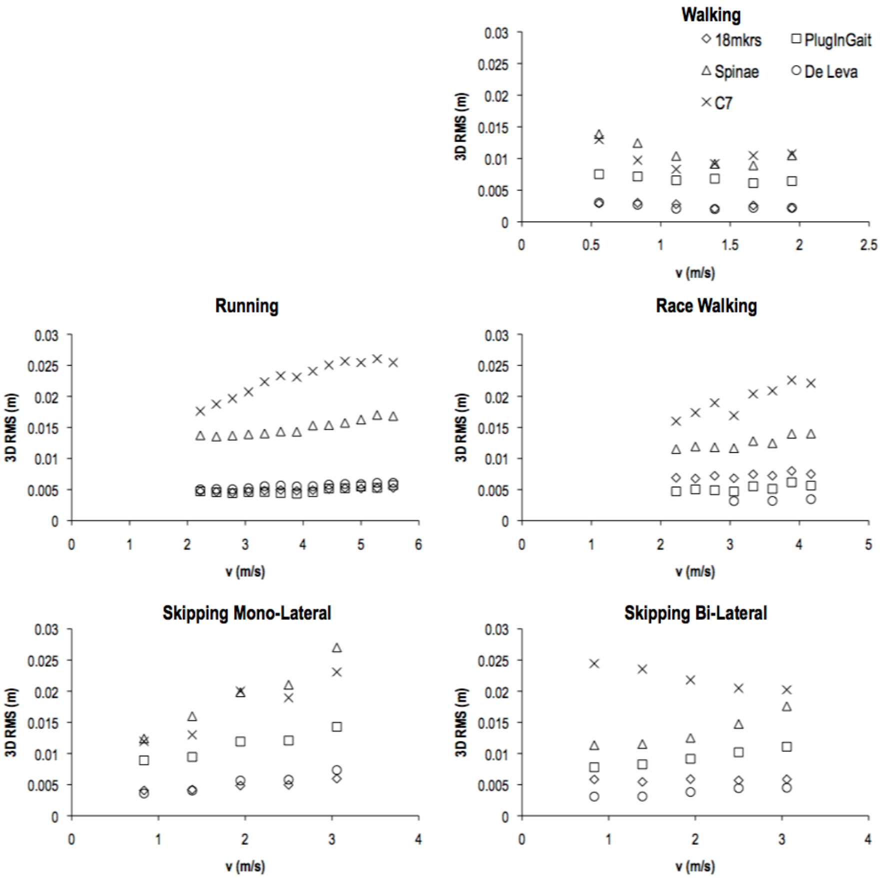

Figure 2. 3D RMS (m) from GRF to the Inverse Dynamics models as a function of speed in the gaits. Standard deviations have been omitted for clarity.

W_{EXT} (J/(kg m)) as function of speed in all gaits is shown in figure 3. In walking the trend is similar for all model even if the degree of over/under-estimation differs between Inverse and Direct Dynamics. In running, Spinae and C7 largely over and under-estimate values, whereas other Direct Dynamics models overestimate with similar values. In race walking, 18mkr and De Leva are closed to GRF, on the contrary PlugInGait and C7 underestimate and Spinae largely overestimate. Skipping Bi-lateral was well described by all methods, whereas in mono-lateral especially at high speed values were different.

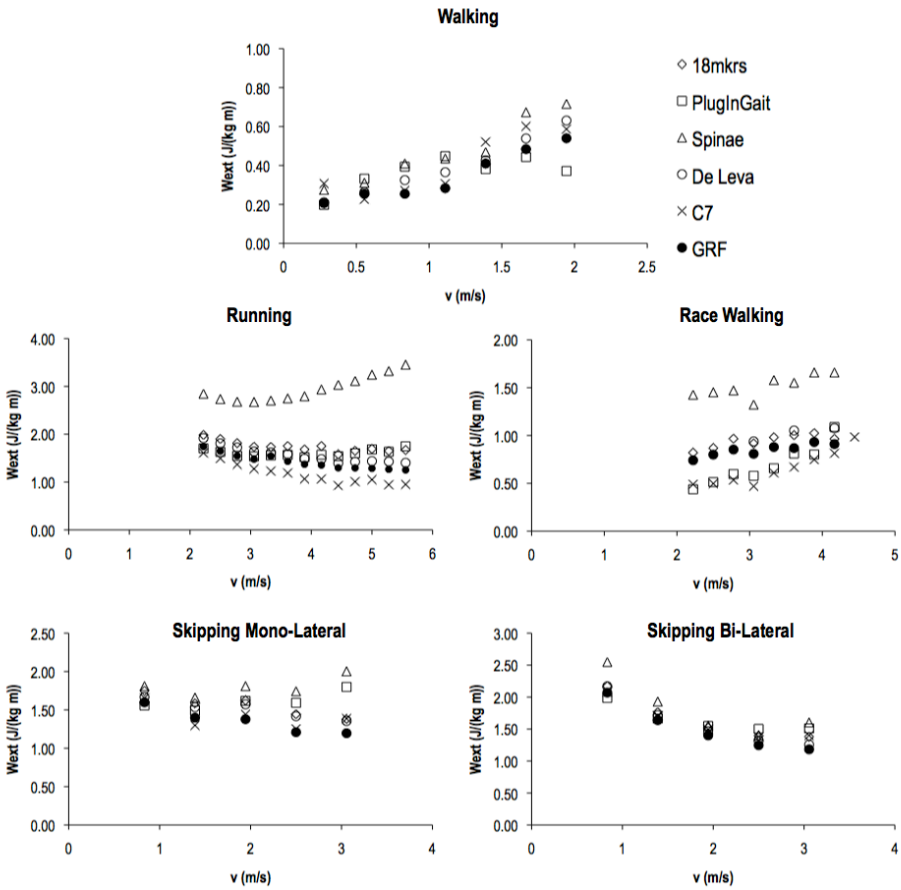

Figure 3. W_{EXT} (J/(kg m)) as a function of speed calculated with the different computational BCoM methods in the gaits. Standard deviations have been omitted for clarity.

Energy Recovery (%) as function of speed in all gaits is shown in figure 4. In walking the pattern is well resemble except for PlugInGait and C7 at high speeds. Running displays low values in all methods even if the percentage difference from GRF in C7 and PlugInGait is great. In race walking, Spinae and De Leva well match GRF data, 18mkr quite overestimate at low speeds, whereas PlugInGait and C7 largely overestimate Energy Recovery values at all speeds. In mono-lateral skipping there is the major difference between Direct and Inverse Dynamics with a near 10% underestimation by De Leva and 18mkr and overestimation of Spinae and C7. Conversely in Bi-lateral 18mkr and De Leva match GRF data, Spinae still overestimates and C7 and PlugInGait underestimate Direct Dynamics results.

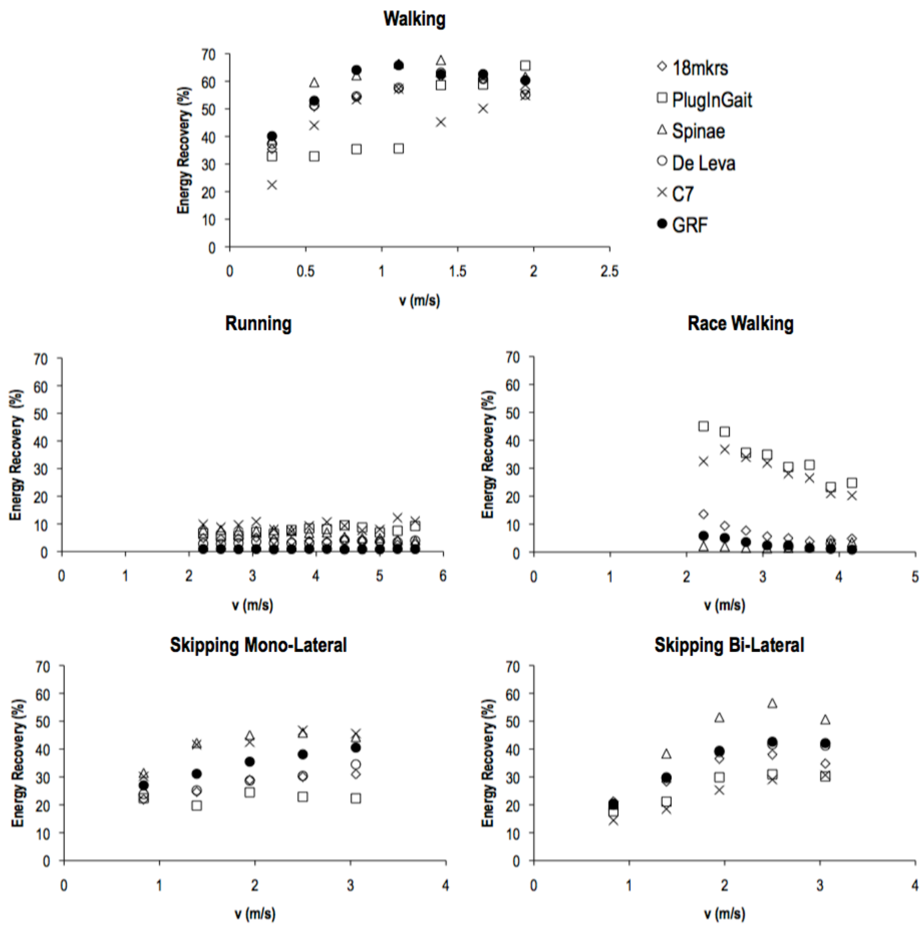

Figure 4. Energy Recovery (%) as a function of speed calculated with the different computational BCoM methods in the gaits. Standard deviations have been omitted for clarity.

The W_{INT} calculation of body segment with respect to BCoM computed from GRF and 18mkr is presented in figure 5, in all gaits values lays on the identity line, hence there are no differences between the two different computational methods.

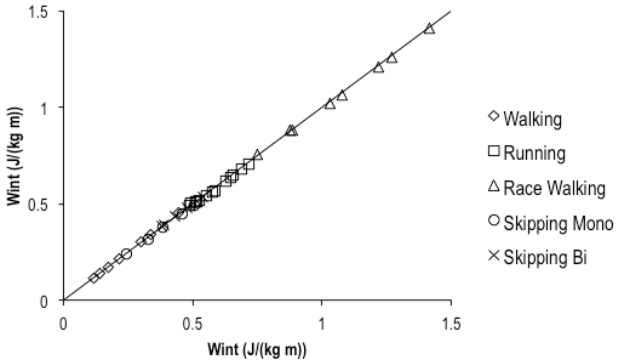

Figure 5. W_{INT} (J/(kg m)) values calculated respect to Direct Dynamic BCoM vs. W_{INT} calculated respect to Inverse Dynamic BCoM are shown in different gaits, continuous line represents identity line. Standard deviations have been omitted for clarity.

Discussion

The aim of this paper was to compare Inverse to Direct Dynamics in order to validate Inverse Dynamics on the whole range of speeds of the human gaits and evaluate if these methods could be used interchangeably.

The validation was made first by comparing the 3D trajectory of BCoM.

The 3D RMS (m) shows that two whole body models, 18mkr and De Leva, even based on different anthropometric tables, better fitted walking, running and skipping (mono- or bi-lateral). On the contrary, one marker placed on the trunk (C7) or the mean of pelvis showed a trajectory far from Direct Dynamics. In 18mkr and De Leva, 3D RMS in almost all gaits is speed independent, which can be considered a systematic error and could be subtracted in order to obtain GRF trajectory, whereas C7 and Spinae 3D RMS increases with speed. These results, higher 3D RMS and speed dependency of simplistic models highlights that it is indispensable to include limbs for describing the real (3D) BCoM trajectory. In addition, using a whole body model the 3D RMS value among gaits is very similar, and this strongly support the idea that the human body can be modeled as a rigid multi-segment object, except for race walking.

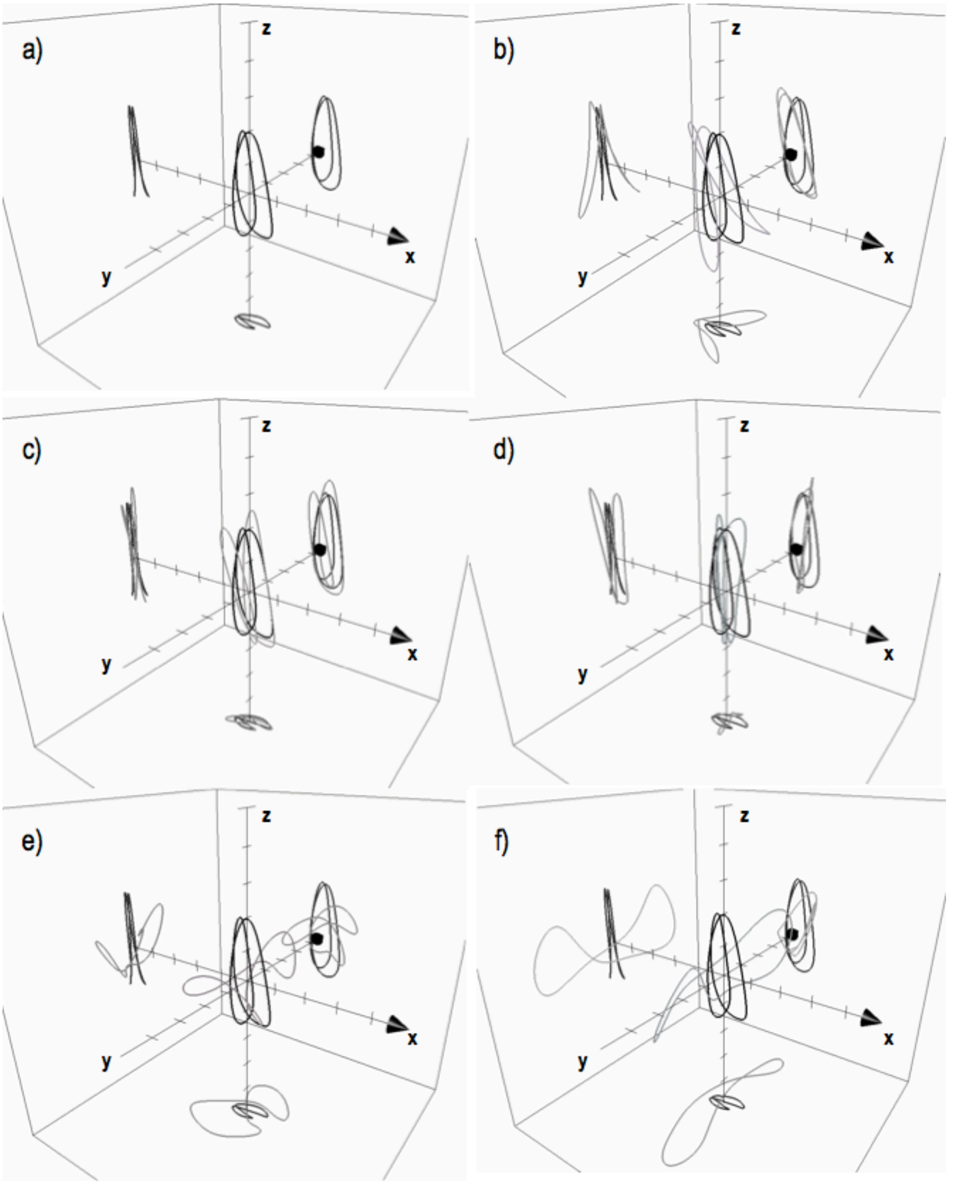

Figure 6. The 3D BCoM contour of the mean race walking stride at 3.89 m/s is shown; arrow on x-axis indicates progression direction, one thick 0.01 m. **a)** 3D BCoM contour from GRF and in dark in the other panel for comparison; **b)** light line 3D BCoM contour from 18mkr; **c)** light line, 3D BCoM contour from De Leva; **d)** light line, 3D BCoM contour from PlugInGait; **e)** light line, 3D BCoM contour from Spiane; **f)** light line, 3D BCoM contour from C7.

Since 3D RMS seemed very closed also in race walking strides, even if inspectional visual observation (Fig. 6) showed some differences we decided to refine 3D RMS by normalising for the volume of the contour. In figure 7 it is evident that the same 3D RMS normalized for the contour volume is effectively much larger in race walking because of the little 3D excursion of BCoM. Hence race walking BCoM trajectory obtained with Inverse Dynamics is biased. In order to understand the reasons of this error, we looked at race walking kinematics: it is evident that the trunk does not act like a rigid segment, in fact it changes considerably its length during a whole stride cycle in the frontal and sagittal plane. This length variation can result in an error on the 18mkr BCoM calculation since trunk is modeled as one unique segment linking shoulder-great trochanter. However even when the trunk is split, and the modeling refined, in three parts as occurs in De Leva the trajectory becomes closer to Direct Dynamics (3D RMS) but its shape does not resemble GRF. This methodological issue needs future studies and for the moment race walking BCoM trajectory from Inverse Dynamics should not be used.

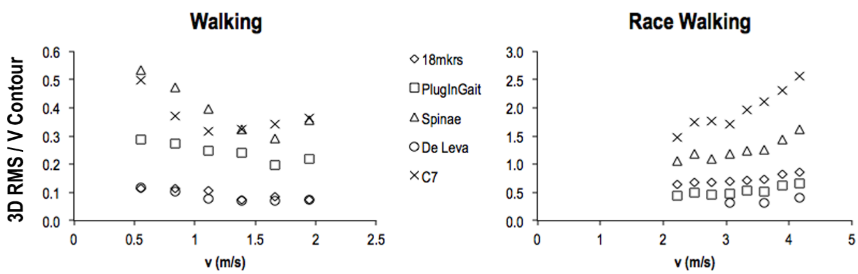

Figure 7. 3D RMS normalised for 3D BCoM contour volume in walking and race walking as a function of speed in the Inverse Dynamics methods. Standard deviations have been omitted for clarity.

One step ahead in gait analysis is to consider related parameters to BCoM trajectory such as the work done by muscles to complete the stride; W_{EXT}.

In all gaits, the different models matched W_{EXT} with different under/overestimation percentage. In walking, W_{EXT} values are the lowest and an apparently small overestimation of Spinae, for example, gets values doubled than GRF causing misunderstanding both in data comparison and successive analyses. In running, Spinae showed disagreement again, whereas full body models only slightly overestimated W_{EXT} values. This is primarily due to the total energy fluctuation during flight. In fact while GRF shows a constant energy value during flight (forces are zero), body segments rotations caused variation on BCoM, causing an increase in total energy, which ultimately gives greater values of W_{EXT}. Despite the difference in trajectory, 18mkr and De Leva well matched W_{EXT} data of race walking data, whereas Spinae, C7 and PlugInGait data are too far from GRF. When considering also Energy Recovery, 18mkr displays a greater percentage, which means that potential and kinetic energy are quite out of phase, differently form GRF, remarking again the low confidence of Inverse Dynamics calculation. With few exceptions the W_{EXT} over estimation of 18mkr and De Leva, when compared with GRF, is constant in the whole range of speeds in all gaits, this could allow to subtract the known value to Inverse Dynamics W_{EXT} in order to obtain better estimates and a more reliable Inverse/Direct Dynamics comparison.

As expected from the literature (Willems et al. 1995), Energy Recovery showed its maximal values in walking, minimal in running and race walking, whereas skipping had intermediate values, slightly higher in Bi-lateral. The analysed models show various differences from GRF and in some cases also different trends as occur for C7 among gaits. Energy Recovery is also an indicator of the goodness of the model by describing potential and kinetics energies variations, the striking result comes from race walking, C7 and PlugInGait calculated values near walking, whereas GRF is proximal to zero highlighting Inverse Dynamics problems.

PlugInGait is the only model not custom made; it is one of the Nexus outputs (Vicon cameras software), compared with GRF it resembles BCoM trajectory in running, but poorly all other gaits, first of all walking. Since the shape is so different in walking compared to other model we think that the only possible explanation of this discrepancy is a biased calculation of joints centre, from which segment length and mass are computed, which could cause a wrong calculation of the whole centre of mass. It has to be pointed out that on Plug-In Gait Manual it is written 'Please note that this centre of mass algorithm has not been clinically tested, and may be misleading in some clinical situations', however Gutierrez-Farewik et al. (2006) used and validate it in walking children and actually, it is misleading also in non-clinical application. Such a good match in BCoM trajectory during running allows us to conclude that the problem is more visible in gaits with double contact such as walking and skipping, whereas long flight time, where BCoM should resemble only the 'ballistic trajectory', seems to 'help' the BCoM computation by diminishing errors.

Our 3D RMS data in walking are comparable with Whittle (1997) and Eames et al. (1999) where centre of pelvis overestimate BCoM trajectory compared to both GRF and a whole body kinematic model (Vicon Body Builder). Gutierrez-Farewik et al. (2006) using a Plug-In Gait model found a greater RMS than present study. However, they validated the model since they said that mass sensitivity error and integration speed constant in vertical axis and the constant speed assumption for antero-posterior axis could give major errors to GRF compared with Inverse Dynamics. In this study, the treadmill gave more accurate and reliable values than a stride caught with two platforms and we cannot consider valid such huge 3D RMS. As for running, even focusing only on vertical axis, Spinae never match whole body model as suggested by Gullstrand et al. (2009).

Last point regards W_{INT}, it is clear that the small discrepancy between GRF and 18mkr in BCoM trajectory and W_{EXT} does not affect W_{INT}. Moreover it is interesting to note that nor when BCoM trajectory is totally far from GRF, as occurs in race walking, W_{INT} calculation is biased, validating the kinematics approach without the need of force plates and allowing the usage of W_{INT} also in race walking in comparison with other gaits. Race walking values are as in walking and running speed dependent and almost 2 times higher than running at the same speed.

With this paper we can validate Inverse Dynamics only when a whole body kinematics model is employed, and 12 segments are enough, since human gaits features at increasing speed are well described, the only exception regards race walking.

Second study

This article has been published in the journal 'Planetary and Space Science' 74:142-145 (2012) as 'The energetics and mechanics of level and gradient skipping: Preliminary results for a potential gait of choice in low gravity environments.' Minetti AE, Pavei G and Biancardi CM.

The energetics and mechanics of level and gradient skipping: Preliminary results for a potential gait of choice in low gravity environments.

Abstract

Walking and running in low gravity cannot be used at useful speeds, while 'skipping', a gait displayed by kids and spontaneously adopted by astronauts of Apollo missions, proved to have the potential to become the gait of choice in that condition. In this paper the previous biomechanical and metabolic analysis of level skipping is extended to positive and negative gradients, in normal gravity. The results confirm at all gradients the higher (average) ground reaction force during the contact phase, with respect to running at the same speed, which would allow confidently facing the Lunar surface where the dust and regoliths affect, in addition to a lower gravity, the locomotion dynamics. Metabolic data, other gait variables related to the mechanical work done and the locomotor/respiratory coupling have also been investigated.

Keywords: Bioenergetics, Biomechanics, Skipping, Low gravity, Speed, Gradient.

Nomenclature:

C_S	metabolic cost of transport
VO_2	oxygen consumption
RQ	respiratory quotient
BCoM	whole body centre of mass
PE	mechanical gravitational potential energy
KE	mechanical kinetic energy

TE	total mechanical energy
W_{EXT}	mechanical external work
W_{INT}	mechanical internal work
W_{TOT}	total mechanical work
SF	stride frequency
BW	body weight
t_{flight}	fraction of the flight phase with respect to the stride period
$F_{vert.contact}$	average vertical force during the contact phase

Introduction

'Skipping' is an alternative gait pattern with respect to walking and running, mostly adopted on Earth by kids while playing and occasionally by adults when fast cornering or while descending stairs. Similar to walking, there is a stride phase when the two feet are placed on the ground in succession and, similar to running, there is a flight phase after that. Also mechanically, the time course of the body centre of mass energies shows features shared by walking (pendulum like exchange) and running (elastic bounce) features (Minetti, 1998).

Due to the peculiarly long flight phase, skipping was noticed as a gait where the vertical ground reaction force was higher than running at the same speed. In addition, the unilateral skipping (characterised by the sequence LEFT-RIGHT-FLIGHT or RIGHT-LEFT-FLIGHT) supposedly involved a lower 'internal mechanical work', associated to the acceleration of limbs with respect to the body centre of mass. These observations suggested that this 3rd human gait (adopted also by lemurs and dynamically similar to quadrupedal gallop) could be beneficially exploited when limb movement is somewhat restricted and while moving on slippery terrains. There was no surprise then, when examining NASA footage of Apollo missions, to see astronauts performing skipping on the Moon surface (Minetti, 1998a).

Skipping as a potential gait of choice in hypogravity has been further confirmed recently by simulation studies (Ackermann and van den Bogert 2012) demonstrating dynamical and energetic advantages related to it.

The perspective of future Lunar (and Martian) explorations, as foreseen in the Scientific Preparations for Lunar Exploration meeting (6–7 February 2012, ESA/ESTEC, Noordwijk, the Netherlands), (Minetti et al. 2012) encouraged us, as the former investigators of this

gait, to design a research road map to extend the analysis of both metabolic and mechanical aspects in the attempt to provide astronauts with a feasible set of recommendations to face those environments.
Also, during that conference, the many manifested concerns about regoliths and lunar dust pose additional needs of specific research on the selection of proper gaits that would circumvent the ground friction issue.
The results presented in this paper deal with the extension to gradient skipping in Earth gravity of our previous methodology and results (Minetti, 1998a). The next research steps will incorporate partial load suspension simulations and ultimate experiments of skipping on a treadmill during parabolic flights.

Material and Methods

Six subjects (3 males and 3 females, 28 ± 4 yr, 1.64 ± 0.04 m stature, 66 ± 13.5 kg mass) performed unilateral skipping on a motorised treadmill (Woodway, Germany) at different gradients (0%, + 5%, + 10%, - 5%, - 10%, and - 15%, where, for example, + 10% indicates the steepness corresponding to moving 10 m upward for every 100 m travelled horizontally) and speeds (range 1.39–3.06 m s^{-1}, step 0.56 m s^{-1}). Subjects were experienced with skipping and treadmill use. The experimental protocol started with the subjects quietly standing for 5 min; then they walked for 4 min at increasing speeds on the level first. Successively the same speed sequence was administered at increasing downhill and uphill gradients. The study was approved by the Ethics Committee of the University of Milan, and participants, after becoming aware of the potential risks involved in the experimental sessions, gave their informed consent.
Metabolic data were collected with a portable metabograph ($K4b^2$, Cosmed, Italy) both at rest and during the last minute of the four necessary to achieve the steady state. Skipping cost of transport (C_s, J kg^{-1} m^{-1}), i.e. the amount of metabolic energy necessary to move 1 kg of body mass for a distance of 1 m (analogous to the amount of gasoline used to move 1 mile in cars), was calculated by dividing net oxygen consumption VO_2 (average exercise VO_2 - basal VO_2, mlO_2 kg^{-1} min^{-1}) by the progression speed (m s^{-1}). The unit conversion from ml O_2 to metabolic J was achieved by considering the mean RQ (respiratory quotient, representing the ratio of the amount of CO_2 produced to O_2 consumed) for each acquisition. Ten minutes of rest elapsed between trials in order to reach a complete recovery.

Three-dimensional kinematics of skipping subjects were measured by means of 18 reflective markers captured by 8 infrared cameras (Vicon MX, UK) at a sampling rate of 100 Hz. Markers were placed symmetrically on anatomical landmarks of the body (occipital lobe, glenohumeral axis, elbow, hand, great trochanter, femoral condyle, lateral malleolus, calcaneus, 5th metatarsus) in order to approximate its multi-segment moving structure. Anthropometric data such as the fractional mass of all segments, the relative position of their centre of mass and the moment of inertia along the main axis (Winter 1979) were used to determine the 3D position of the whole body centre of mass (BCoM). A custom program written in LabVIEW (National Instruments, US) calculated, for each instant within the strides, the 3D position of BCoM, its potential (PE, J), kinetic energy on three axes (KEx, progression, KEz, vertical, KEy, medio-lateral, J) and energy recovery, i.e. an index of how much energy is saved by exchanging potential and kinetic energies of BCoM as in a pendulum (Saibene and Minetti, 2001). From these data the total mechanical energy of BCoM (TE=PE+KEx+KEy+KEz) was computed, and the sum of its positive changes within each stride resulted in the mechanical external (W_{EXT}, Cavagna and Kaneko 1977), defined as the work necessary to lift and accelerate BCoM to maintain locomotion. In addition, the work necessary to accelerate limbs with respect to BCoM, called mechanical internal work (W_{INT}, Cavagna and Kaneko, 1977), and the total work done ($W_{TOT} = W_{EXT} + W_{INT}$) were calculated in comparable unit of C_S (mechanical J kg^{-1} m^{-1}). Also, the 3D Lissajous contour of BCoM trajectory, a 3D closed loop of its path in local coordinates (Minetti et al. 2011), was obtained.

Results

Some of the results are presented as average ± SD. Metabolic measurements showed that Cs decreases with speed and negative gradients, while it increases with positive gradients. Due to the limited gradient range, we fit the data with a paraboloid equation:

$$C_s = -4.016 \text{ speed} + 0.655 \text{ speed}^2 + 10.858 \text{ gradient} + 34.167 \text{ gradient}^2 + 10.563$$

$$R^2 = 0.997 \quad P<0.001$$

When compared to the metabolic cost of locomotion in similar conditions (Ardigó et al. 2003), C_s resulted to be always higher than walking and running.

The Respiratory quotient (RQ) was found to sit on a plane of equation:

$$RQ = 0.065\ \text{speed} + 0.598\ \text{gradient} + 0.841 \quad R^2 = 0.389 \quad P<0.001$$

Subjects adopted 'left' skipping, where the footfall sequence is FLIGHT-RIGHT-LEFT. From kinematics we found that the contact duration of the trailing (RIGHT) foot, namely the first to touch the ground after a flight, is significantly longer than the leading (LEFT) one (44.0 ± 5.0 % of the stride duration vs. 40.6 ± 6.4 %, respectively, paired t-test P = $2.39 \cdot 10^{-10}$).

The stride frequency (SF, Hz) resulted to vary according to:

$$SF = 0.170\ \text{speed} + 0.422\ \text{gradient} + 1.163 \quad R^2 = 0.217\ P<0.001$$

The average vertical ground reaction force during the contact phase, expressed in body weight (BW) and calculated as:

$$F_{vert.contact} = 1/(1-t_{flight})$$

where t_{flight} is the fraction of the stride at which the body is off the ground, was found to vary according to

$$F_{vert.contact} = 0.181\ \text{speed} - 0.529\ \text{gradient} + 0.898 \quad R^2 = 0.942 \quad P<0.001$$

Inspectively and statistically, both the external and internal work seemed to be better described by a curvilinear surface such as the paraboloids:

$$W_{EXT} = -0.039\ \text{speed} - 0.091\ \text{speed}^2 + 6.085\ \text{gradient} + 22.033\ \text{gradient}^2 + 2.196$$
$$R^2 = 0.971 \quad P<0.001$$

$$W_{INT} = 0.206\ \text{speed} - 0.022\ \text{speed}^2 + 0.594\ \text{gradient} + 3.459\ \text{gradient}^2 + 0.238$$
$$R^2 = 0.936 \quad P<0.001$$

so that the total mechanical work, obtained by adding W_{EXT} and W_{INT}, was fit by

$$W_{TOT} = 0.166\ \text{speed} - 0.113\ \text{speed}^2 + 6.679\ \text{gradient} + 25.492\ \text{gradient}^2 + 2.434$$
$$R^2 = 0.960 \quad P<0.001$$

The ratio between W_{TOT} and C_s provides an estimate of the 'apparent' efficiency of skipping. This resulted to be almost speed and gradient independent, with an average value of 0.43 ± 0.04 (a CV of 8.7%).

The ability to exchange potential and kinetic energies, obtained both via a pendulum-like dynamics during the contact phase and ballistically during the flight, an extension of the concept introduced by Cavagna and Kaneko (1977), has been estimated as:

$$\text{recovery\%} = 4.463\ \text{speed} - 83.020\ \text{gradient} + 19.267 \quad R^2 = 0.938 \quad P<0.001$$

In synthesis, the different trends of the above variables with respect to speed and gradient are summarized in table 1.

We also evaluated the locomotor/respiratory coupling by dividing the stride frequency by the breathing rate, as measured by the metabograph. We obtain a value of 2.200 ± 0.486, suggesting that subjects decided, on average, to breath once every two strides. The variability shown by these data in the investigated gradient/speed ranges, though, reveals a lack of convergence to a strict 2:1 stride/breath ratio.

	Speed	Gradient
Metabolic Cost (C_s)	-*(=)	+*(+)
RQ	+*	+*
$F_{\text{vert.contact}}$	+*	-*
W_{EXT}	- (=)	+(=)
W_{INT}	+*(+)	+*(+)
W_{TOT}	-	+*
recovery%	+*	-*
stride frequency (SF)	+*(+)	=*(+)

Table 1: Speed and gradient dependencies of the listed variables for skipping. Positive (+) and negative (-) relationships are accompanied by an asterisk to indicate that regression coefficients were found to be significantly different from zero. Trends in brackets refer to running.

Discussion

Almost 50 years ago, investigators started challenging human locomotion in different gravitational environments (Margaria and Cavagna 1964). They rightly concluded that on the Moon walking should be possible only at very low speeds, and that 'terrestrial' running would have been mechanically difficult to adopt there. Later on, a general predicting equation for the speed of dynamically equivalent walking in hetero-gravity has been proposed and validated (Minetti 2001a, 2001b). Despite the limitations imposed by low gravity to the most common forms of human locomotion, other papers (Minetti 1998a) pointed out that skipping, another gait particularly used during the childhood, shows mechanical features that could make it a gait of choice in that environment. Footage from Apollo missions confirmed that suggestion and, by revealing that unilateral skipping was frequently adopted on the moon surface, indicated the likely constraint imposed by space suits on lower limb oscillation and, consequently, the need to minimize the mechanical internal work.

A number of investigations are needed to verify the appropriateness of skipping as a gait of choice on low gravity celestial bodies:

1) mechanics and energetics of level uni- and bilateral skipping at 1g (Minetti 1998a),

2) mechanics and energetics of level and gradient unilateral skipping at 1g (this paper),

3) mechanics and energetics of level and gradient unilateral skipping at Lunar and Martian gravities by means of body weight suspension,

4) mechanics of level (and gradient) unilateral skipping at Lunar and Martian gravities by means of parabolic flights,

the last two being the next projects in a row. In the rest of this section we will compare skipping to running on Earth, as the two locomotion types are both considered 'bouncing' gaits.

The metabolic results of the present investigation confirm that skipping is quite expensive on Earth, being C_S up to 30% higher than in running (Figure 1) and, as witnessed by the high RQ values, demanding remarkable metabolic power despite of the relatively low speed. We also noticed at all gradients the tendency of C_S to decrease with speed, a feature only paralleled by jumping kangaroos. A rule of thumb for the absolute cost of transport on Earth is that it varies proportionally to the extra load imposed to the body. Thus it can be expected that on the Moon the total metabolic energy spent to travel a unit distance will be much smaller, allowing faster speeds for the same metabolic rate. The quantitative aspects of these predictions will be addressed by studies 3 and 4 because the gait dynamics in low gravity is still unknown, and it could limit the feasible speed range.

Our subjects adopted a left unilateral skipping and a high statistically significant increase in the trailing (right) foot contact duration was found. Although quite small, a similar longer contact was also found in the hoof contact of the trailing limb of the hind propulsive pair in many galloping species (Biancardi and Minetti 2012). This confirms that quadrupedal gallop is dynamically similar to bipedal skipping (Minetti 1998a).

Stride frequency was higher at all speeds and gradients in skipping than in running (SF_R, Minetti et al. 1993), where data is fitted by the equation:

$$SF_R = 0.093 \text{ speed} + 0.404 \text{ gradient} + 1.177 \quad R^2 = 0.776 \quad P<0.001$$

but, most importantly, the average vertical ground reaction force during the contact phase was also always higher in skipping. Data for running ($F_{vert.contact.R}$, BW) were obtained as:

$$F_{vert.contact.R} = 0.093 \text{ speed} - 0.212 \text{ gradient} + 1.001 \quad R^2 = 0.773 \quad P<0.001$$

This confirms and expands the concept that 'at the same speed' there is a gait that involves a higher ground reaction force than running. Such a higher force, in presence of similar horizontal ground reaction forces (needed to propel at the same speed), generates a more vertical resultant vector, which could be beneficial when a slippery terrain needs to be faced.

On the Moon (and other celestial objects) this seems to be the case, with the lunar dust and regoliths certainly affecting the static and dynamic friction coefficients. In preparation for study 3 we will attempt to estimate those coefficients by analysing NASA footage of astronauts and vehicle motion during surface operations.

On the Earth, $F_{vert.contact}$ is supposed to become similar in skipping and running only at very low speeds and very high gradients. The two regression surfaces meet at the line (Figure 2):

$$\text{gradient} = 0.162 \text{ speed} - 0.011$$

The investigated gradients in this study range similarly to the ones reported for the lunar surface. Radar measurements (Tyler and Simpson 1970) resulted in unidirectional rms slopes of 3.5 %, 5.2 %, and 10.5 % for Mare Fecunditatis and Oceanus Procellarum. Laser altimeters (Rosenburg et al. 2011) provided a slope range of the Lunar surface from 3.5% to 13.3% for Maria and Highlands, respectively. The ability to skip faster on the Moon, due to the combination of the same metabolic power and a lower C_S, will most likely involve higher $F_{vert.contact}$ than running, by assuring a better grip (high friction) on the surface.

Friction has often been reported as a problem on return from the Moon. To quote Gene Cernan (Apollo 17 Technical debrief): "I think probably the most aggravating, restricting facets of lunar surface explorations is the dust and its adherence to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be and it's restrictive friction-like action to everything it gets on.". The troubles likely extend to locomotion.

It is interesting to notice that W_{EXT} show the same trends of C_S, in terms of speed and gradient dependencies (see Table 1). The same occurs with other terrestrial gaits as walking and running, suggesting that the work to raise and accelerate the body centre of mass (W_{EXT}) is the major determinant of the overall energy expenditure. A lower W_{INT}, necessary to accelerate limbs with respect to the body centre of mass, than obtained in a previous study (Minetti, 1998) was expected, as unilateral skipping involves a limited oscillation of lower limbs when compared to the bilateral version. Here we found values that seem of the same order of magnitude. In addition, the efficiency of skipping, i.e. the ratio between W_{TOT} and C_S, due to a similar gradient and speed dependencies was found to be quite constant across all locomotor conditions. Its average value, being 0.18 higher than the muscle efficiency (Woledge et al. 1985), indicates that some mechanical energy is stored and released by tendons and other elastic structures during the strides at all gradients, as it was previously shown just for level skipping (Minetti 1998a).

Finally, skipping likely represents one of the few viable locomotion alternatives in low gravity conditions. It needs to be fully understood on Earth and in simulations before being able to instruct and even train astronauts about how to locomote in such conditions. Apart from other biomechanical and bioenergetic studies that will be conducted to complete the picture, the implications of wearing a pressurized space suit will also be considered. Actually, pneumatic limbs could behave similarly to arthropodal exoskeletal appendices where flexion is operated by muscles and extension results to be assisted by a fluid pressure increase inside the limb.

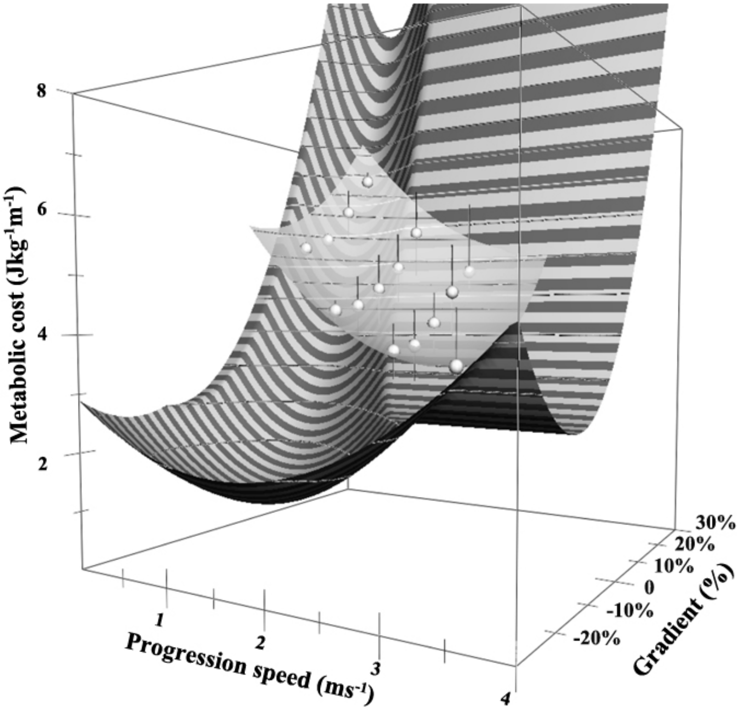

Figure 1. The 3D graph shows the cost of transport (vertical axis) of skipping at different speed and gradients (horizontal axis). The surface represents the cost of walking and running, which of the two is minimal, for sake of comparison.

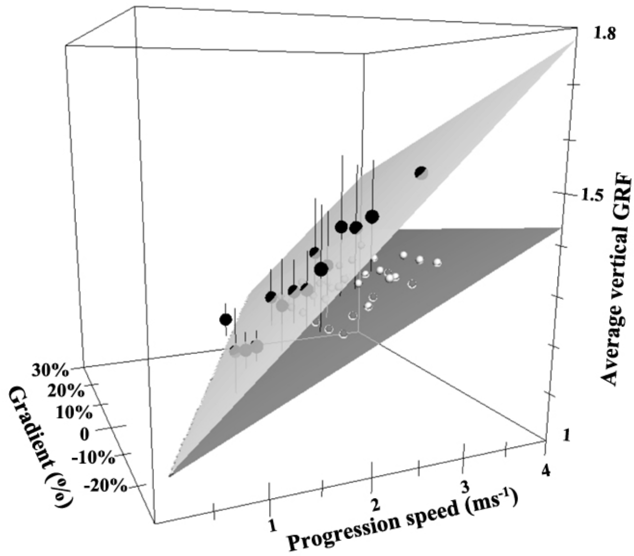

Figure 2. The 3D graph shows the average vertical ground reaction force (GFR) during the contact phase, expressed in body weights (BW) for running and skipping. The planes are the best fitting surfaces for the two sets of data.

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Third study

This article has been submitted as 'Skipping vs. Running as the bipedal gait of choice in hypogravity'. Pavei G, Biancardi CM and Minetti AE.

Skipping vs. Running as the bipedal gait of choice in hypogravity

Abstract

Hypogravity challenges bipedal locomotion in its common forms. However as previously theoretically and empirically suggested, humans can rely on 'skipping', a less common gait available as a functional vestigium of quadrupedal gallop, to confidently move when gravity is much lower than on Earth. We set up a 17 m tall cavaedium with a bungee rubber body-suspension system and a treadmill to investigate the metabolic cost and the biomechanics of low-gravity locomotion. Differently from the cost of terrestrial skipping, which is 40% higher than running, Lunar simulation showed the same economy for the two bouncing gaits (on Mars running is still metabolically less expensive), which approaches typical walking values on Earth (2 J/(kg m)). Our study also reveals that on the Moon skipping could be the gait of choice due to a lower mechanical work to move the lower limbs and the space suit, and suggests an improved motor control during the ground (regoliths)-boot interaction.

Keywords: Locomotion, low gravity, cost of transport, work, efficiency

Introduction

Despite of the apparently slow timescale of space exploration, evolutionary changes genetically adapting our body to different gravitational environments take much longer, and humans (and, eventually, their legged pets) will have to rely on the actual musculo-skeletal system when trying to locomote on other planets.

The usual gait repertoire is challenged by a change in gravity. Walking, the mechanics of which is based on the exchange of potential and kinetic energy of the body centre of mass (BCoM), as occurring in a pendulum (Cavagna et al. 1963), is impaired in low gravity (Cavagna et al. 1998, 2000). The theory of dynamic similarity (Alexander 1989) states that when pendulum-like dynamics is involved, the speed of movement has to scale with the ratio between the planet and Earth's gravity raised to the power of 0.5. Thus, despite the 'facilitating' lower body weight experienced in low gravity, the operative speed range of walking is very much reduced (40% on the Moon). The change in dynamically similar speeds, experimentally simulated at different gravities, has been shown to follow that theory (Minetti 2001b, Ivanenko et al. 201). Even running, which mechanically resembles a pogo-stick where BCoM (kinetic + potential) energy exchanges with elastic energy (tendon length changes) at each bounce, has also been predicted as an impaired locomotion when the body weight reduces, with a top speed of only 3.3 m/s on the Moon (Margaria & Cavagna 1964).

Skipping is the third, almost neglected, human gait characterized by the two feet getting in contact with the ground one after the other, followed by the flight phase. Kids use it for fun, adults adopt it sometimes when descending stairs or during cornering, and its mechanical paradigm is a combination of the pendulum and the pogo-stick (Minetti 1998a). From the footfall perspective, a biped performing unilateral skipping (e.g. Right-Left-Flight) moves exactly as the fore or hind pairs of limbs of a galloping quadruped. The first investigation on this gait pointed out that the ratio between contact phase and stride time, lower on Earth than in running at the same speed, was associated to a higher vertical ground reaction force (hence higher friction with the slippery terrain) and this could partly explain the observation of Apollo astronauts adopting skipping while searching for the most appropriate Lunar gait (see the movie in Supplementary material). That study also showed that, differently from horses where galloping is as economical as trotting (corresponding to bipedal running (Minetti et al. 1999)), the metabolic cost of transport on Earth was up to 40% higher in skipping than in running, requiring a high aerobic power even at slow speed (Minetti 1998a, Minetti et al. 2012).

Ackermann and Van Den Bogert (2012) recently designed a mathematical model searching for the least effort, or least fatiguing, locomotion type depending on the gravity conditions. They found that at speeds of 1.1 and 2.0 m/s skipping is the preferable gait on the Moon, while on Mars the least effort is associated to walking at slow speeds and mainly to running at high speeds.

Although quite encouraging, all the previous results do not help to assess the metabolic sustainability of running and skipping in low gravity, a task needing steady-state measurements of oxygen consumption that could not be achieved in 30 s lasting experimental sessions of parabolic flights reproducing given levels of gravity.

The aim of this study was to calculate biomechanical parameters and metabolic cost of the three human gaits in simulated low gravity conditions that would ensure steady state measurements.

Material and Methods

Heterogravity Laboratory

The cavaedium is a narrow (3 x 3 m) and tall (17 m) space inside the Human Physiology building where a motorized treadmill (PPS 55Ortho, Woodway, Germany) has been installed on the floor, and a body suspension device hung up to a mobile pulley on the top of the ceiling. The suspension device is formed by two bungee jumping rubber bands (Exploring Outdoor srl, Italy), with rest length 4 m and stiffness 92.7 N/m, linked in-series by an inextensible short cable (Gottifredi & Maffioli, Italy, Dyneema SK78, ø 4 mm, L 1.2 m), working on the top pulley. One end of the rubber band was fixed to the wall, while the other end was connected to a harness. The mobile pulley could be lifted or lowered by means of a suspension cable connected to a motorized winch (E.C.E., Italy, 750 W), to unload the body by the desired vertical force checked by means of a balance (Vandoni Salus srl, Italy), and a force transducer (REP Transducers, TS 300 kg, Italy), positioned in-series with the suspension cable. Differently from most of the hypo-gravity simulators (e.g. as He et al. 1991), the pulley is located so far above the subject (16 m) as to reduce to a minimum the horizontal forces that could be generated by the (small) forward-backward and lateral displacement during locomotion on the treadmill (with the Moon gravity, a horizontal move of 0.03 m with respect to pulley resulted in an additional Fx or Fy of 0.92 N, which represents 0.4% and 0.7% of the peak push force during terrestrial stance, respectively (Nilsson & Thorstensson 1989)). Also, the cavaedium height allow to use just one pulley to accommodate a 20 m (10 m x 2 when extended) rubber band, with benefits in terms of low friction and displacement-independence of the vertical force (for a dz of 0.2 m, Fz varied by 5 N when the system was set for the Moon gravity). Although this apparatus quite accurately reproduces the low-gravity condition by applying to BCoM a constant vertical force, it is important to consider that pendulum-like dynamics of swinging limbs is affected by Earth gravity (Ivanenko et al 2011, Cavagna & Margaria 1964, He et al. 1991).

Subjects

Thirteen subjects (7 females and 6 males, 23.3 ± 3.3 yr, 1.70 ± 0.07 m height, 62.4 ± 10.0 kg mass; mean ± SD) took part to the study. The study was approved by the Ethics Committee of the University of Milan, and participants, after becoming aware of the potential risks involved in the experimental sessions, gave their informed consent. Subjects undertook two familiarisation sessions to get used with gaits on low gravity conditions where, particularly at high speeds, balance and proprioception were largely involved. After familiarisation subjects came to the laboratory 5 times in order to complete the metabolic and kinematic protocol.

Experimental protocol

Walking, skipping and running were tested on Earth (1g) and two simulated gravity level, Mars (0.36g) and Moon (0.16g) at different speeds from 0.83 to 3.61 m/s.

Metabolic measurements

Each experimental session started with 8 minutes of basal $\dot{V}_{O_2}$ ($mlO_2/(kg\ min)$) assessment after which subjects started locomoting on the treadmill. Data acquisition lasted 4 minutes in order to reach a steady state for $\dot{V}_{O_2}$. Respiratory gas were analysed breath by breath with a portable metabograph (K4b^2, Cosmed, Italy), and the cost of transport (C), i.e. the metabolic energy to move 1 kg of body mass for a distance of 1 m was estimated from the data collected during the last minute by dividing the measured net O_2 consumption (total-basal $\dot{V}_{O_2}$) by the progression speed. Each metabolic level resulted to be submaximal (RQ <1) and RQ caloric equivalent (J/mlO_2) was multiplied to O_2 consumption for C calculation. Terrestrial running and skipping data in figure 1, 2 and 6 are from Ardigó et al. (1995) and from Minetti et al. (2012) respectively.

Kinematics

3D body motion was sampled by a 8 cameras system (Vicon MX, Oxford Metrics, UK) measuring at a sampling rate of 100 Hz the spatial coordinates of 18 reflective markers located on the main joint centres. Each acquisition lasted 1 minute and the time course of BCoM position was computed from a 11-segment model (Minetti et al. 1993) based on Dempster inertial parameters of body segments (Winter 1979). From BCoM 3D trajectory the time course of potential (PE) and kinetic (KE) energies were computed in order to obtain the Total Mechanical Energy (TE=PE+KE). The summation of all increases in TE time course constitutes the positive external work (W_{EXT}), and represents the positive work necessary to accelerate and lift BCoM (Cavagna & Kaneko 1977). The work necessary to rotate and accelerate limbs with respect to BCoM (W_{INT}) (Cavagna & Kaneko 1977, Minetti 1998b) was also calculated and summed to W_{EXT} in order to obtain the total mechanical work (W_{TOT}). The ratio between W_{TOT} and C was used to estimate locomotion efficiency. All data have been analysed with purposely written Labview programs (release 10, National Instruments, US).

Statistics

Data were compared between speeds and gravity level using one way ANOVA with significance set at $p < 0.05$ and Bonferroni post hoc test. Statistical analyses were performed with SPSS v20 (IBM, USA).

Results

Cost of Transport

The results show a 18% reduction in metabolic cost of walking when low gravity is simulated (Figure 1a), although the difference was not significant. The U shape of walking cost was similar between Earth and Mars/Moon, with minimum not different among planets.

The cost of transport of bouncing gaits, (Figure 1b) decreased at low gravity much more in skipping than in running, and on the Moon the two gaits involve almost the same economy. C was statistically lower in each gravity condition in both gaits ($p<0.001$ Earth vs. low gravity pooled; $p<0.01$ Mars vs. Moon), and running cost retained its speed independency. The same aerobic power (say, 30 mlO_2/(kg min)) allowing to skip on Earth only at very low speeds (Minetti et al 2012, e.g., 1.4 m/s or 5.0 km/h) is enough to steadily run and skip on the Moon at 4.2 m/s (or 15.1 km/h), with a gain in performance (3x for skipping, 2x for running) that could be considered almost speed- and, within some limits, additional load mass-independent.

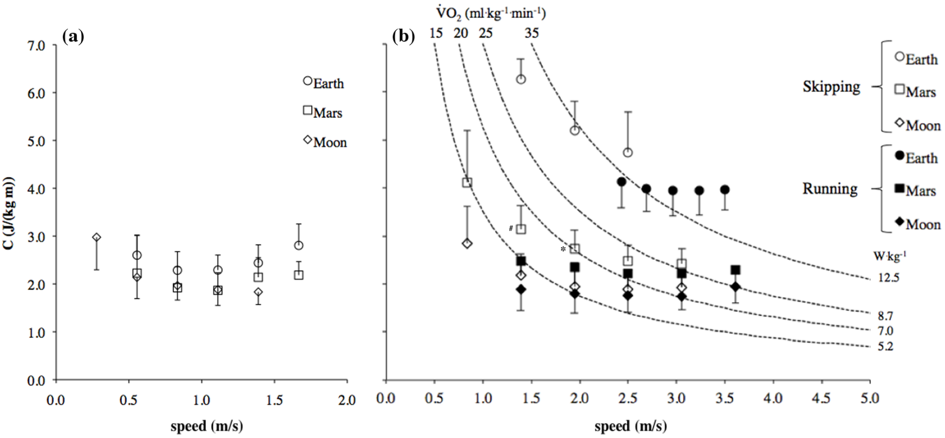

Figure 1: Cost of transport as a function of speed and gravity. **a)** Walking on Earth (circles), Mars (squares) and Moon (diamond). **b)** Running and skipping (solid and open symbols, respectively) on Earth (circles), Mars (squares) and Moon (diamond). Vertical lines represent SD, * $p<0.05$, # $p<0.01$. Iso-power hyperbolas (dashed curves) represent different sustainable aerobic levels (including basal metabolism, expressed both as mlO2/(kg min) or W/kg of body mass).

Biomechanical Parameters

The mechanical external, internal and total work in the three gaits and gravity conditions are plotted against speed in figure 2.

W_{EXT} for walking significantly increased with speed at all gravities, but mean values significantly decreased when gravity was low ($p<0.001$ Earth vs. low gravity), mainly due to the PE reduction. When Skipping in hypo-gravity W_{EXT} seemed speed independent, with a significant reduction compared to Earth: 3-fold lower on Mars and 4-fold on Moon ($p<0.001$ Earth vs. low gravity pooled; $p<0.01$ Mars vs. Moon). In running the external work significantly increased with speed at lunar gravity, while in the other cases it was speed independent. As in skipping the reduction among gravity was significant ($p<0.001$ Earth vs. low gravity pooled; $p<0.001$ Mars vs. Moon). Walking values were always smaller than bouncing gaits, whereas skipping values became slightly lower than running in low gravity conditions.

W_{INT} in walking increased with speed at all gravities but decreased as average when gravity was low ($p<0.01$) without significant difference between low gravity levels. As for skipping W_{INT} increased significantly with speed on Earth and Mars and decreased significantly with low gravity ($p<0.001$ Earth vs. low gravity pooled; $p<0.01$ Mars vs. Moon). The same trend was found in running ($p<0.001$ Earth vs. low gravity pooled; $p<0.05$ Mars vs. Moon). Skipping W_{INT} was higher than running on Earth, but became lower than it when gravity was decreased.

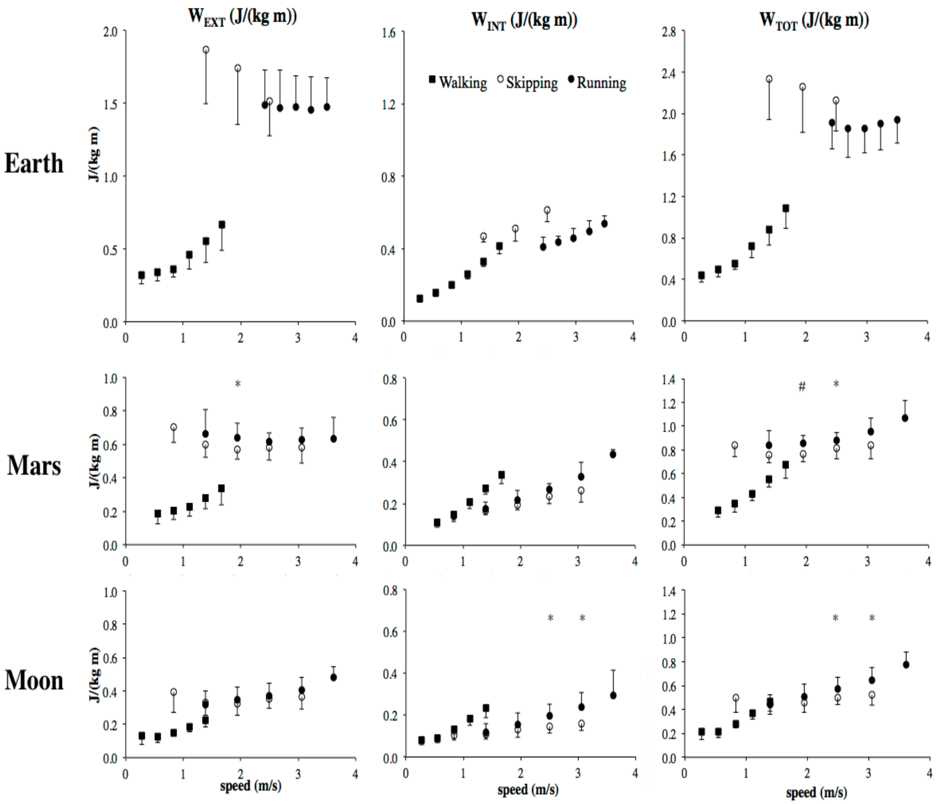

Figure 2: Mechanical work. External work (W_{EXT} J/(kg m)), 'Kinematic' internal work (W_{INT} J/(kg m)) and Total work (W_{TOT} J/(kg m)) of walking (solid square), running (solid circles) and skipping (open circles) as a function of speed on Earth and on simulated Mars and Moon. Vertical lines represent SD, * $p<0.05$, # $p<0.01$.

Average W_{TOT} as the sum of W_{EXT} and W_{INT} decreased with low gravity in walking ($p<0.001$ Earth vs. low gravity pooled; $p<0.05$ Mars vs. Moon at fastest speed) and in bouncing gaits ($p<0.001$ Earth vs. low gravity pooled; $p<0.01$ Mars vs. Moon) with a tendency of skipping towards speed independence.

Energy Recovery (figure 3) in walking showed a maximum on Earth at intermediate speed. At Mars gravity the maximum value was lower and the decay at faster speed higher than on Earth. On Moon, the maximum recovery was reached at slower speed and its value was even smaller, with a steeper decay over speed. When speed was normalised for dynamic similarity, the maximal Energy Recovery value was reached at similar Froude number. In skipping Energy Recovery was almost constant on Earth (around 25%), and its maximal value increased slightly, but not significantly, when gravity decreased, reaching on Moon walking values.

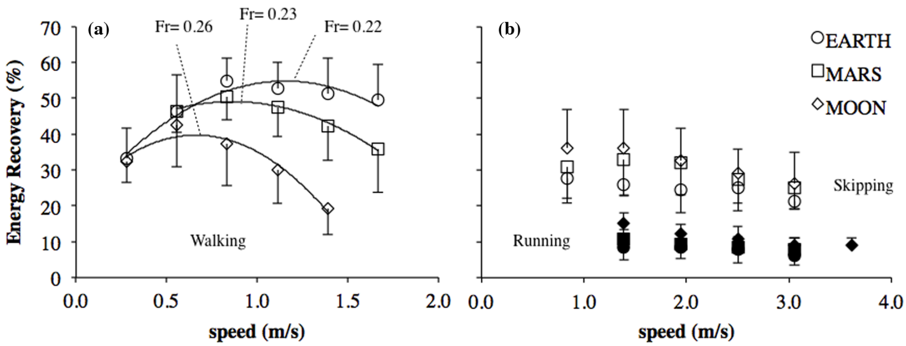

Figure 3: Energy Recovery (%) as a function of speed and gravity. **a)** Walking on Earth (circles), Mars (squares) and Moon (diamond). Data are fit with a quadratic function and its maximum normalised as Froude Number (Fr). **b)** Running and skipping (solid and open symbols, respectively) on Earth (circles), Mars (squares) and Moon (diamond). Vertical lines represent SD.

Stride Frequency (SF, figure 4) in walking significantly increased with speed but was gravity independent. Skipping SF was speed independent in hypo-gravity and differences among gravities were statistically significant at all speeds ($p<0.001$ Earth vs. low gravity pooled; $p<0.01$ Mars vs. Moon). Running values were speed dependent, and decreased with low gravity ($p<0.01$ Earth-low gravity) however SF was not different between Mars and Moon.

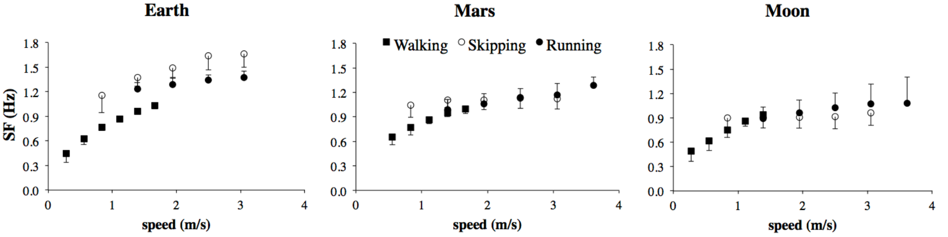

Figure 4: Stride frequency (Hz) as a function of speed and gravity in the three gaits: walking (solid square), running (solid circles) and skipping (open circles). Vertical lines represent SD.

Low gravity running involves a smaller descent of the body centre of mass during the contact phase, relative to the resting height, than on Earth (figure 5). On the other hand, hypogravity skipping maintains a remarkable descent of BCoM and shows a higher gain in vertical displacement (x2 on the Moon) during the flight phase than in running.

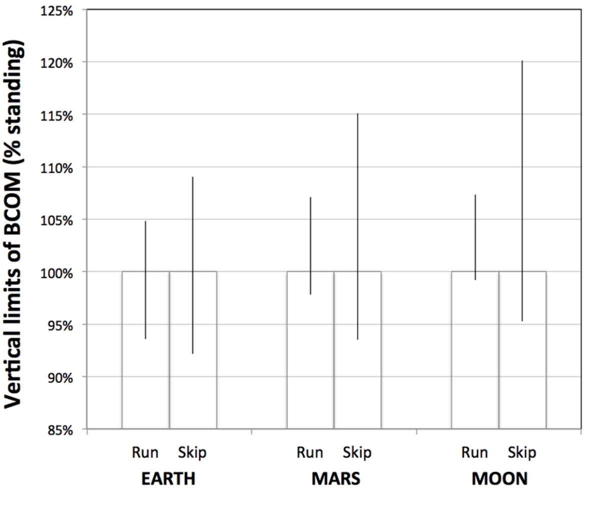

Figure 5: Vertical BCoM range. Descent (during contact) and ascent (during flight) of the body centre of mass on Earth and on simulated Mars and Moon, as a percentage of the standing value, of running and skipping.

Efficiency

Locomotion efficiency, i.e. the ratio between total work performed (W_{TOT}) and energy consumed (C) increases with speed at all gravities in every gait (figure 6), however average efficiency decreases up to 49% ($p<0.01$), 32% ($p<0.001$) and 43% ($p<0.001$) of the values on Earth in walking, running and skipping, respectively, as gravity gets small. The efficiency of skipping in hypogravity is closer to terrestrial walking levels, and running efficiency in hypogravity reaches values of about 40%, approaching muscular efficiency and much lower than the highest efficiency reported on Earth.

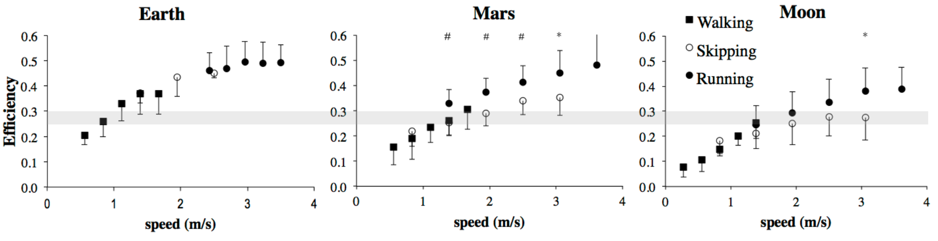

Figure 6: Efficiency of walking (solid square), running (solid circles) and skipping (open circles) as a function of speed on Earth and on simulated Mars and Moon. Grey band indicates the muscular efficiency (0.25-0.30). Vertical lines represent SD * $p<0.05$, # $p<0.01$.

Discussion

From a metabolic perspective our results show that bouncing gaits benefit in low gravity more than walking, and that skipping reports the highest gain in cost reduction. This could partly explain astronauts' choice during Apollo 14 and 17 missions of skipping gait while moving on the Moon (see the movie in Supplementary material).

Differently from previous studies (Farley & McMahon 1991, Worth & Prescott 1966) we found no statistical differences in walking cost when gravity is low. An overall reduction of 18% was found between Earth and hypogravity values without differences between Mars and Moon. The simulation apparatus could be the cause of such a discrepancy. Teunissen et al. (2007) found a higher running cost in hypogravity than Farley and McMahon (1991) and they attributed the discrepancy to adopting a longer cord length over subject head. A short length could in fact help the subject maintaining balance and the elasticity of the rope could store and release more elastic energy during the fore-aft movements acting like a spring. These combined interactions potentially result in a reduced cost.

In our experimental set up the pivot point was at least 12 m over subject's head and, as mentioned, the maximum induced fore-aft or medio-lateral force would have been 0.92 N, hence we could conclude that our subjects experienced a very small bias from the apparatus, and that the measured C is one of the most reliable metabolic estimate from a (sufficiently long lasting) low gravity simulation. It has to be considered also that, unless astronauts will operate inside a pressurized dome, our metabolic results should be corrected for the additional mass of the space suit (around 117 kg), with a predictable decrease in speed, for the same available metabolic power.

The mechanical external work was reduced by low gravity mostly due to the potential energy in the three gaits. However walking was negative affected by this reduction, since the pendulum like saving mechanism needs the exchange between potential and kinetic energies in order to minimize muscular work. As showed in figure 3, Energy Recovery decreased at low gravity, and its peak value occurred at slower speeds pointing also out a likely higher muscular work, which ultimately affects metabolic cost. These mechanical data are consistent with Cavagna et al. experiments (1998, 2000) collected during parabolic flights and the predictions from the dynamic similarity theory (Minetti 2001b). The internal work decreased only between Earth and low gravity planets, whereas stride frequency was not different among gravities in walking witnessing the adoption of similar stride lengths.

We will focus the rest of the discussion on the bouncing gaits since they were never been analysed in such detail before, they are quite affected by gravity and because of their relevance in fast locomotion.

Figure 2 shows that kinematic W_{INT}, diminishes in low gravity (stride frequency effect) and that running and skipping are quite similar on Earth, with a tendency in skipping to be smaller at lower gravities, due to a further reduction of stride frequency. The internal work can also be predicted by a model equation (Minetti 1998b) that has as input variables the progression speed, stride frequency, duty factor and a (compound) estimate of the inertial characteristics of upper and lower limbs. The predictive equation can also be used to evaluate the determinants of measured internal work changes in terms of the involved variables. In the present investigation, for example, the -67.5% change of running W_{INT} when on the Moon can be partly explained by the 24.7% decrease in stride frequency and the 38.8% lowering of the duty factor (which sums up to a -41.1%

expected change in the model equation). In addition, the angular excursion of lower limb segments was found to be 40% lower than on Earth. In addition to the 'kinematic' W_{INT} reduction, we can expect a much smaller 'frictional' W_{INT} due to the minimal overlap between swinging thighs (with or without space suit) on the sagittal plane, which is a peculiar aspect of unilateral skipping.

Although not directly reflecting the exploitation of tendons in storing and releasing the elastic energy particularly needed in bouncing gaits, it is intuitive that a very small BCoM descent (figure 5), with respect to the straight limb posture, could not be associated to a substantial mechanical energy saving based on that strategy. Less 'compressed' limbs (running) need to rely more on muscle contraction to achieve a high take-off speed, which will be penalized anyway by the lack of the power-amplification effect operated by tendon stretch/recoil. This is one of the reasons for the decrease of 'apparent' efficiency of the two bouncing gaits in low gravity (figure 6). Locomotion efficiency is often called 'apparent' when it exceeds muscle efficiency (0.25-0.30, Woledge et al. 1985). An efficiency greater than the 'engine' value often reflects a numerator inflated by some positive work that should not be considered, being the consequence of a previously 'absorbed' negative work. This is mainly caused by elastic structures as muscle tendons and the arch of the foot (Ker et al. 1987), which are stretched during the first half of the contact time and recoil thereafter. Thus, the excess of 'apparent' efficiency with respect to 0.25-0.30, particularly high in galloping horses, can be regarded as an index of elastic contribution to locomotion (Minetti et al 1999). Along this line of thought, running and skipping show a decrease of elastic contribution in low gravity, and on the Moon their efficiency does not need to be called 'apparent' any more, albeit at very high speeds. Our muscle-tendon units, with the muscle acting almost isometrically during bounces on Earth, similarly to other running bipeds (Roberts et al 1997), cannot cope efficiently with the reduced load as the stiffness of the inert component remains the same in all gravitational environments. This implies a smaller elastic stretch (and recoil) in hypogravity, as indirectly shown for running in figure 5.

Other mechanical differences between the two bouncing gaits deal with the specialization of lower limbs. In running, the contact phase of each limb incorporates a braking action followed by a propulsive push before the flight (Minetti 1998a). In skipping that sequence is reversed, and propulsion and braking are separately provided by trailing and leading limbs (Minetti 1998a, Fiers et al. 2013), respectively, whose consecutive action on the ground prepares the flight phase along a more extended base of support (figure 7). The foot contact pattern suggests that skipping could be the preferred gait in terms of movement control. Besides space suits, also lunar dust (regoliths) and its low friction coefficient are likely to hinder locomotion. When compared to running, the duty factor (Alexander 1989) (df, i.e. the fraction of the stride duration at which each foot is on the ground) is significantly shorter, at the same progression speed. Since the average vertical ground reaction force (Fz) during the entire stride has to equal body weight, the shorter the contact phase, the higher the average force each limb must exert during that phase (mean Fz = $m \cdot g/(2 \cdot df)$) (Minetti 1998a). Our kinematic measurements of simulated locomotion on the Moon show that mean Fz is significantly greater (+26.0 ± 7.4 %) in skipping than in running, at the same progression speed. That is quite beneficial in hypogravity as the risk of skidding on regoliths is reduced by a higher vertical force, not followed by a corresponding increase in horizontal force (take-off angle, with respect to the horizontal line in the sagittal plane, was found to be 77.1 ± 4.9° and 73.1 ± 3.1° for running and 82.4 ± 4.7° and 77.8 ± 5.7° for skipping, at 9 and 11 km/h, respectively). Also, yaw control is supposed to be assisted by the peculiar footfall of skipping. The temporally contiguous placement of trailing and leading foot on the ground greatly prolongs the distance travelled by the Centre of Pressure (CoP, i.e. the ideal point on the ground where all the forces are 'summarized' at each instant of the contact phase). Although quite fast moving from the trailing and the leading foot (figure 7), CoP persistence on the ground allows, particularly in slippery conditions, to re-adjust the overall BCoM direction of motion before the flight. In running such a correction has to be made (twice) within shorter (single) contact times during which BCoM travels a shorter distance. In addition, fewer muscles would be involved in the correction.

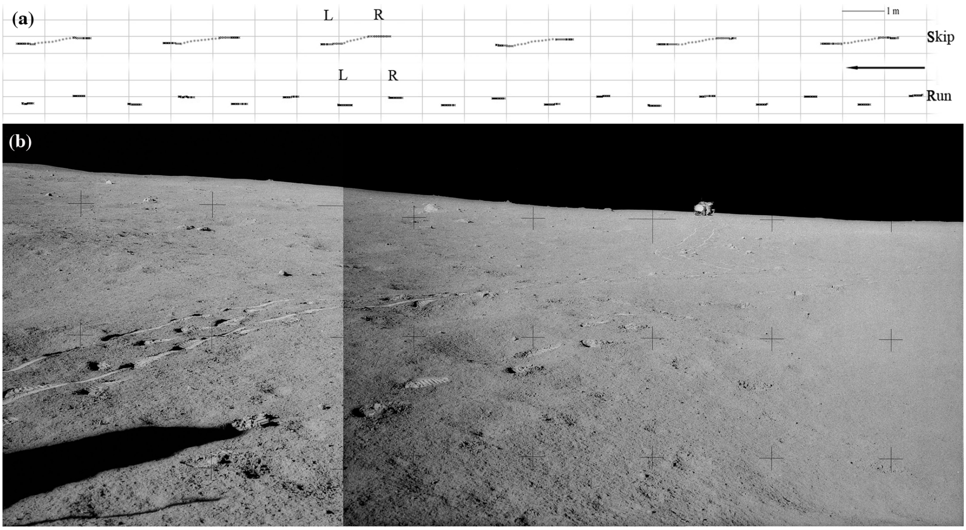

Figure 7: Lunar boot prints. **a)** Foot casts of running (lower trace) and unilateral left skipping (upper trace). Skipping Centre of Pressure is shown as a dotted curve (in running its path is confined within a single cast). **b)** skipping boot prints of Alan Shepard during Apollo 14 Mission (www.hq.nasa.org). Body is moving towards bottom-left, showing asymmetry of the trailing and leading (the deeper) cast. The trail starts (from the right) with a right skip (left-right-flight) then, after 3-4 strides, switches to left skip (right-left-flight), as racehorses periodically do with right and left gallop on the straight corridors of the track (Biancardi & Minetti 2012b).

Early biomechanists (Cavagna et al 1963) assimilated legged locomotion to a rimless wheel, where limbs are the wheel spokes. In bouncing gaits, we need to imagine a bouncing rimless wheel. Differently from running, skipping uses 2 adjacent spokes during the bounce, making the contact paradigm more similar to a normal rolling wheel.

It is likely that skipping will be used also for steering and moving in circles on the Lunar surface, as it is an asymmetrical gait quadrupeds deterministically use to turn (in the direction of the leading limb of the front pair first, then followed by the hind limbs), as observable in show jumping competition. Most of the locomotion repertoire in legged species is based on right-left symmetrical limb movements. Gallop and skipping are exceptions, and some evidences point out that asymmetry can be an advantage. When modellistically searching for energetic optimality, limb movement symmetry is often found (Srinivasan 2011): symmetric inverted pendulum walking gait always requires less work than an inverted pendulum gait with asymmetric steps. Rather, the same study indicated that in springy bipeds with compliant tendons, both symmetric (running) and asymmetric gaits (such as skipping) were optimal.

In synthesis, even by losing most of their elastic components, fast bipedal gaits from our ancestral repertoire are metabolically sustainable in low gravity. Our measurements show that unilateral skipping, an expensive gallop-derived bipedal gait on Earth used by lemurs and (vestigially) by humans, could be the preferred locomotion in low gravity due to the much lowered metabolic cost and to its peculiar biomechanics, which minimise mechanical work and enhance grip control on a slippery ground. The timing of biological evolution cannot cope with space exploration, but specific training programs will potentiate astronauts' muscles to better assist a locomotion pattern that is already embedded in the Central Pattern Generator. Differently from quadrupedal pets (and lemurs), probably already at ease with hypogravitational locomotion, humans will be confident by only restoring an almost dismissed gait.

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Supplementary Material

The Mechanical Internal Work

The mechanical internal work of locomotion (W_{INT}), needed to move limbs (particularly) when they do not cause any displacement of the body centre of mass, has two main components none of which depends on gravity: 1) kinematic W_{INT}, due to the translational and rotational speed change of each body segment, and 2) frictional W_{INT}, due to the dissipative forces acting within the joints or among segments. Both components depend on the stride frequency (which ultimately affects the speed change) but frictional W_{INT} is there even when kinematic W_{INT} is zero (i.e. when segments move at constant speed with respect to BCoM. In movement biomechanics the role of 'kinematic' W_{INT} (the measurable component) is still debated.

The 'kinematic' form of the mechanical internal work derives from the König's Theorem, stating that the total kinetic energy of a multi-segment system is the sum of a) the kinetic energy of the body centre of mass (BCoM) and b) the kinetic energy of each segment, calculated from the linear speed relative to BCoM and from the rotational speed of the segment. The idea is to take into account the reciprocal movements of segments not resulting in a BCoM displacement. In locomotion biomechanics, the first component is incorporated in the calculation of the mechanical (positive) external work, which is defined as the work necessary to lift and accelerate the BCoM, while the second component, further processed as to consider hypothesized energy exchanges among segments from the same limb, is called the Mechanical Internal Work (W_{INT}).

The 'frictional' component of the mechanical internal work is supposed to be an important, albeit very difficult to assess, component of the total work (and of the metabolic expenditure). It is related to the energy dissipation occurring among biological tissues, e.g. loaded sinoviae, ligaments, fasciae, muscular containment structures, skin of sliding body segments, etc. Even when we kinematically measure segments (reciprocally) moving at a constant speed, there could be some work again friction muscles need to supply to maintain them in motion. Since work rate against friction strongly depends on speed, and in cycling segments speed is closely related to pedalling frequency, Minetti (2011) suggested that in cycling the excess of metabolic expenditure measured during pedalling frequency manipulation experiments is explained by both the measured 'kinematic' and the almost unmeasurable 'frictional' part, which is supposed to be associated to the former.

Such a frictional component of W_{INT} has nothing to share with the work against dust friction, which is an additional component of W_{EXT}. When analysing real locomotion on the Moon, the effects of dust might be taken into account. As pointed out by Gene Cernan, in the Apollo 17 Technical Debrief, "... the most aggravating restricting facets of lunar surface explorations is the dust [regoliths] and its adherence to everything ... , suit material, and its friction-like action... you're continually fighting the dust problem both inside and outside the spacecraft."

Additional information sources

Video footage, photographs, transcriptions and annotations from NASA, accessible also via Google Earth, are of crucial importance to realize the locomotor conditions on the Moon (Figure S1). Interesting movies on this subject are visible by means of YouTube at the following addresses:

http://youtu.be/DYDqB_G5PCo?t=8m24s, http://youtu.be/wuaBluY1rhc?t=5m36s, http://youtu.be/7tFP4ha2IOQ?t=27s, http://youtu.be/wuaBluY1rhc?t=0m57s, http://youtu.be/JC-cyoqKjpQ?t=47m41s

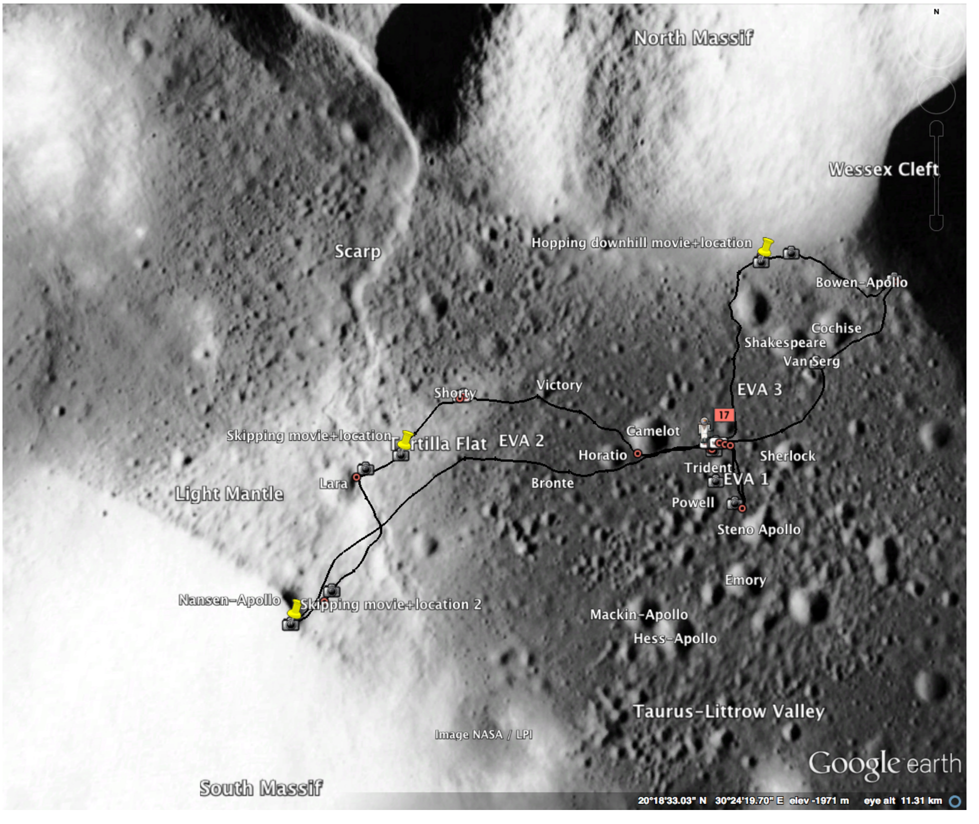
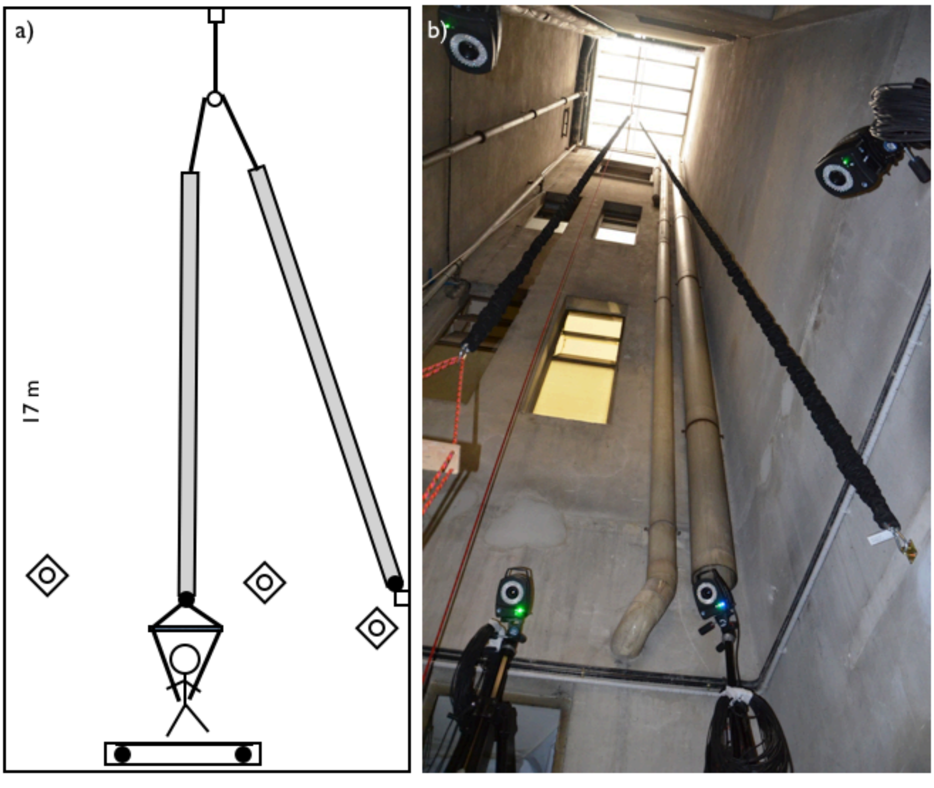


Figure S1: Maps of skipping traverse on the Moon, from Google Earth. Yellow needles indicates places where skipping video in supplementary materials were recorded.



Picture 1. Low gravity *cavedium*. **a)** schematic diagram of "cavedium" set up: the subject is free to move on a treadmill while is unloaded by two bungee cords, they are connected in series by an inextensible dynema rope, which roll over a frictionless pulley. **b)** real set up with stretched bungee cords and Vicon cameras during one acquisition.

Picture 2. Section cover of BBC Science (March 2013) with a subject skipping in the "low gravity cavedium" at Moon gravity. Vicon cameras are collecting kinematics data, whereas metabolic data are collected by the portable unit (white one on subject chest) while subject is breathing (blue mask). The harness is connected to the bungee cords via the red rope.

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Appendix: Side Scientific Production

Papers

G. Pavei, D. Cazzola, A. La Torre and A.E. Minetti (2014). The biomechanics of race walking: Literature overview and new insights. European Journal of Sport Science, 14:661-670. (doi:10.1080/17461391.2013.878755)

Proceeding of congress

A.E. Minetti, G. Pavei and C.M. Biancardi (2012). Legged locomotion paradigms on Earth can teach humans how to safely extend their progression speed when moving on the Moon. Scientific Preparations for Lunar Exploration, ESA/ESTEC, Noordwijk, the Netherlands 6^{th}-7^{th} February.

G. Merati, A. La Torre, M. Bonato, G. Pavei, S. Bossolasco, L. Galli and P. Cinque. (2012). Parasympathetic tone and its adaptation to aerobic training (Fitwalking®) in HIV patients on anti-retroviral therapy. ACSM 59^{th} Annual Meeting, San Francisco, US 29^{th} May – 2^{nd} June. Med Sci Sports Exerc. 44(5S):S149

S. Porcelli, L. Pugliese, E. Rejc, G. Pavei, M. Bonato, A. La Torre, M. Marzorati and C. Marconi (2012). Did Popeye© know something about nitrates? ACSM 59^{th} Annual Meeting, San Francisco, US 29^{th} May – 2^{nd} June. Med Sci Sports Exerc. 44(5S):S291

M. Bonato, A. La Torre, S. Bossolasco, G. Pavei, G. Merati, L. Galli and P. Cinque (2012). What are the benefits of physical exercise in people with HIV infection? ECSS 17^{th} Annual Congress, Bruges, Belgium 4^{th}-7^{th} July.

G. Pavei, D. Cazzola, A. La Torre and A.E. Minetti. (2012). Body center of mass trajectory shows how race walkers elude "Froude law". ECSS 17^{th} Annual Congress, Bruges, Belgium 4^{th}-7^{th} July. (Young Investigators Award winner, 3^{rd} place Oral Presentation)

G. Pavei, D. Cazzola, A. La Torre and A.E. Minetti. (2012). Body center of mass trajectory shows how race walkers elude "Froude law". JSPfSM 67^{th} Annual Meeting, Gifu City, Japan 14^{th}-16^{th} September. (Invited Oral Presentation)

G. Pavei, D. Cazzola and A.E. Minetti. (2012). The 3D trajectory of the body centre of mass and other mechanical aspects of race walking. SIF 63^{th} Annual Congress, Verona, Italy 21^{st}-23^{rd} September.

A.E. Minetti, G. Pavei and C.M. Biancardi (2012). 'Skipping' as the gait of choice in hypo-gravity: metabolic and biomechanical insights from level and gradient experiments on Earth. SIF 63th Annual Congress, Verona, Italy 21st-23rd September.

M. Bonato, S. Bossolasco, L. Galli, G. Pavei, M. Testa, C. Bertocchi, E. Galvano, G. Balconi, A. Lazzarin, G. Merati, A. La Torre and P. Cinque. (2012). Moderate aerobic exercise (brisk walking) increases bone density in cART-treated persons. Eleventh International Congress on Drug Therapy in HIV Infection, Glosgow, UK 11th-15th November. J Int AIDS Soc. 15(Suppl 4):18318

G. Pavei, D. Cazzola, A. La Torre and A.E. Minetti (2013). A literature overview of Race Walking: is it enough for coaching? International European race walking scientific conference, Dudince, Slovakia 18th May.

M. Bonato, S. Bossolasco, L. Galli, S. Mandola, G. Pavei, M. Testa, C. Bertocchi, E. Galvano, G. Balconi, A. Lazzarin, G. Merati, A. La Torre and P. Cinque. (2013). Brisk walking increases bone mineral density in cART-patients. ECSS 18th Annual Congress, Barcelona, Spain, 26th-29th June.

G. Pavei & A.E. Minetti (2013). Prediction of race time decrease, due to the performance drop-off, in running 3000m to marathon. ECSS 18th Annual Congress, Barcelona, Spain, 26th-29th June.

G. Pavei, A. La Torre and D. Cazzola (2013). Race walking angular displacement at increasing speed. SISMES 5th Nation Congress, Pavia, Italy, 27th – 29th September. Sport Sci Health. 9(Suppl1):S10

G. Pavei, S. Porcelli, E. Rejc, M. Bonato, M. Marzorati, A. La Torre and L. Pugliese (2013). Effects of nitrate supplementation on repeated sprint performance in healthy subjects. SISMES 5th Nation Congress, Pavia, Italy, 27th – 29th September. Sport Sci Health. 9(Suppl1):S35

V. Longo, M. Bonato, S. Bossolasco, L. Galli, A. Caumo, G. Pavei, A. Lazzarin, G. Merati, A. La Torre and P. Cinque (2014). Brisk Walking Improves Inflammatory Markers in cART-Treated Patients. Conference on Retroviruses and Opportunistic Infections (CROI 2014), Boston, US, 3rd – 6th March.

M.Bonato, V. Longo, S. Bossolasco, G. Pavei, L. Galli, G. Merati, A. La Torre and P. Cinque (2014). A pilot study of moderate physical activity in HIV-infected persons receiving anti-HIV drugs: benefits on soluble and cell markers of inflammation. ECSS 19th Annual Congress, Amsterdam, The Netherlands, 2nd – 5th July.

E. Preatoni, D. Cazzola, G. Pavei, A. E. Minetti (2014) Technical skills and movement coordination in elite, national and regional level race walkers. 7^{th} World Congress of Biomechanics, Boston, USA, 6^{th} – 11^{th} July.

G. Pavei, C.M. Biancardi and A.E. Minetti (2014). Biomechanics and bioenergetics of human locomotion in simulated low-gravity. 7^{th} World Congress of Biomechanics, Boston, USA, 6^{th} – 11^{th} July. (Travel awards of European Society of Biomechanics)

A.E. Minetti, C.M. Biancardi and G. Pavei (2014). Giant strides are what you'll take, skipping on the Moon. International Calgary Running Symposium, Calgary, Canada, 14^{th} – 17^{th} August.

Awards

ECSS Young Investigators Award (YIA) winner for oral presentation in Bruges 2012.
European Society of Biomechanics WCB-2014 Travel Awards.

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