External mechanical work of locomotion from inverse dynamics: insight from different body plans

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Abstract— The external mechanical work (W_{EXT}) estimation primarily depends on the trajectory of the body centre of mass (COM_b). Inverse dynamics (ID) provides reliable tools to reconstruct the COM_b position from different kinematic models. We measured and compared the W_{EXT} from a full body model and a simplified one, in human locomotion and in octopedal locomotion of terrestrial spiders, in order to quantify the difference and evaluate the reliability of the latter model. Analyzing the COM_b displacements by means of one or two landmarks fixed to the main body segment can be a simple approximation, useful for different purposes. Conversely, the full models consider the movement of all the body segments, with different complexity levels. In our protocols, the simplified model was a subset of the full model. Therefore, we could collect both in the very same trial, using a motion capture system. Spider kinematic data were collected during free displacements in a calibrated space. Humans performed walking, running, and skipping at different controlled speeds on a treadmill. The simplified model always resulted in a variable, speed dependent, overestimation of the W_{EXT}. 3D kinetic energy of the COM_b was affected more than the potential energy. Therefore, in bouncing gaits like skipping and, on minor extent, running, the differences were proportionally smaller than in walking. In skipping the error was almost constant (30%) throughout the speed range. The error was also affected by the relative weight of the body segments. For estimating the mechanical energy of the COM_b, a full body model is highly recommended, at least in vertebrates.

***Keywords*— Animal locomotion, External mechanical work, Kinematic models, Inverse dynamics.**

***Resumen*—** La estimación del trabajo mecánico externo (W_{EXT}) depende principalmente de la trayectoria del centro de masa corporal (COM_b). Utilizando diferentes modelos cinemáticos es posible reconstruir de forma confiable, mediante herramientas de dinámica inversa, la posición del COM_b. Medimos y comparamos el W_{EXT} calculado por un modelo simple y otro completo, en locomoción bípeda y octópoda, al fin de calcular las diferencias y evaluar la confiabilidad del modelo simplificado. El análisis del desplazamiento del centro de masa a través de uno o dos marcadores fijados en el segmento mayor del cuerpo puede ser una aproximación útil para diferentes propósitos. Inversamente, en un modelo completo se consideran los movimientos de todos, o casi todos, los segmentos corporales. El modelo simplificado fue un subconjunto de marcadores del modelo completo. En tarántulas, los datos fueron colectados durante desplazamientos libres en un espacio especialmente calibrado. Los humanos se desplazaron caminando, corriendo y galopando sobre una cinta caminadora, a diferentes velocidades controladas. Los modelos simplificados siempre sobreestimaron el W_{EXT} de forma dependiente de la velocidad. La energía cinética resultó ser más afectada que la energía potencial. Así, en los patrones con características de rebote como el galope y en menor medida la carrera, las diferencias entre los dos modelos fue menor que en la marcha. En el skipping el error porcentual fue constante en las diferentes velocidades, alrededor del 30%, La diferencia entre los modelos fue influenciada por el peso relativo de los segmentos. Con el propósito de estimar la energía mecánica del COM_b, se recomienda utilizar, al menos en vertebrados, un modelo que incluya los segmentos corporales.

***Palabras clave*— Locomoción animal, Trabajo mecánico externo, Modelos cinemáticos, Dinámica inversa.**

I. INTRODUCTION

The accurate determination of the mechanical work of locomotion is one of the main topics of human and comparative biomechanics. The chemical energy derived from the metabolic processes, also called "metabolic energy", is partially converted, by the muscles during locomotion, in mechanical work. Most of the mechanical work is done, in terrestrial legged locomotion, to rise and reaccelerate the body centre of mass (COM_b): the so-called external work (W_{EXT}). Albeit the internal work (W_{INT}) – i.e. the work done to accelerate and decelerate the body segments with respect to the COM_b – represent the minor part of the total mechanical work [1]. W_{EXT} is related to changes in the total mechanical energy (the sum of kinetic and potential energies) of the COM_b. Speed, gaits and their energy saving mechanisms are among the determinants of the external mechanical work [2], and W_{EXT} can generally be a useful indicator of the metabolic energy expenditure [3].

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In order to compute the changes of kinetic and potential energy over a locomotion cycle, it is indeed necessary to know, or, better, estimate, all the instantaneous positions and velocity of the COM_b. This result can be achieved by integrating over time the force vectors acting on the COM_b, a technique called forward dynamics (FD) [4]. Conversely, inverse dynamics (ID) start from the detection of the 3D positions of body markers, from which the 3D position of the COM_b can be reconstructed, according to a kinematic model, and its velocity derived [4].

Both techniques present pros and cons. FD relies on dynamometric platforms, which main cons, in locomotion studies, is their dimensions, which permit to capture only one or few steps (even in case of several force plate in series) [5]. Treadmills equipped with force transducers are expensive and not always available in biomechanics and gait labs. Despite FD is still considered the golden standard for the COM_b determination, the modern motion capture systems are increasingly used, as are able to sample and process kinematic data of hundreds of cycles on a treadmill.

Previous studies from Pavei et al. [4] demonstrated that kinematic models built with 11 to 14 body segments (full body models) permit a reliable reconstruction of the COM_b trajectory during different human gaits. We started from this background to test, on a wider population and a larger number of cycles (strides), the differences in the estimation of the W_{EXT} between a full body model and a simplified one, in human locomotion. Moreover, we tested the same differences in two spider species, processing data available from previous studies [6, 7].

The rise and development of Inertial Motion Units technology in the last years has made these tools available for biomechanics applications. The possibility to bind an accelerometer to an animal or human body would permit the collection of a huge quantity of kinematic data directly in real (wild or field) conditions. In this perspective, the purpose of this work was to verify the reliability and quantify the possible drift or error of estimating mechanical parameters from a single fixed position or from extremely simplified centre of mass models.

II. Materials and Methods

A. Experimental procedure (Humans).

Eight subject, seven males and one female (age 26±3 y; mass 72.7±14.6 kg; height 172±8 cm), were selected to perform 10 trials (4 walking, 3 running, 3 skipping) on a treadmill (T2100, General Electric, USA), at different controlled speeds. The project was approved by the ethics committee of the Centro Universitario Regional Litoral Norte de la Universidad de la República (Exp. # 311170-000521-18), and each subject signed an informed consent, according to the Declaration of Helsinki.

At the beginning of each session, the subject was measured and weighted, and prepared for the kinematic acquisitions. Reflective markers (n = 18) were put on the main joint, defining 11 body segments: trunk with head, arms, forearms with hands, thighs, shanks, and feet [3].

The protocol included walking at 3.0, 4.0, 5.0 and 6.5 kmh^{-1}; running at 6.5, 9.0 and 11.0 kmh^{-1}, and skipping at 5.0, 6.5 and 9.0 kmh^{-1}. Each trial lasted for two minutes, in random sequence. Data were collected for one minute, after the subject came to a regular locomotion.

Experiments were carried out at the Laboratory of Biomechanics and Movements Analyses of the Centro Universitario Litoral Norte of the Universidad de la República, Paysandú, Uruguay.

B. Data sampling and processing.

Kinematic data were collected with a Vicon motion capture system (Oxford Metrics, UK), equipped with 8 Bonita cameras, at a sampling rate of 100 Hz. The coordinate system was set with *x* directed anteroposteriorly, according to the longitudinal axis of the treadmill, and the other axes according to the right-hand rule (*z* as the vertical axis).

Using the described set of markers, two different kinematic models were implemented, a full body centre of mass model based on 11 segments and 18 markers (FM), and an extreme simplified model based on one pelvic segment identified by the two markers located in the great throcanters (SM).

In the former FM, the COM_b 3D positions were computed as the weighted means of the segment's centers of mass (segmental method), in turn determined by means of anthropometric Dempster tables [8]. In the SM, the COM_b was estimated as the medial point between the two trochanters.

Kinematic data were filtered through a "zero-lag" fourth order Butterworth low-pass filter with a cut-off frequency of 6 Hz, embedded in a Nexus 2.5 software routine (Vicon,Oxford Metrics, UK).

C. Mechanical parameters.

All mechanical parameters described here were computed according to [1] and [9]. The time course of the potential energy (Ep) was computed from the z-axis position of the COM_b. From the 3D position of the COM_b were derived velocities and consequently computed the kinetic energies (Ek_x, Ek_y, Ek_z). The total energy of the COM_b (E_{TOT}) is defined as the sum of $Ep + Ek_x + Ek_y + Ek_z$.

The vertical work (W_V), the work done to lift the COM_b, was computed as the sum of the increments of the time course of $Ep + Ek_z$. The horizontal work (W_H), the work done to accelerate the COM_b in the transverse (horizontal) plane, resulted by the sum of the increments of $Ek_x + Ek_y$. Conversely, the external work W_{EXT} was computed as the sum of the increments of E_{TOT}. All mechanical works were expressed for unit mass and distance ($J\ kg^{-1}m^{-1}$) [1].

The phase shift between the curves of $Ep + Ek_z$ and $Ek_x + Ek_y$ determines that the sum of $W_V + W_H$ is greater than W_{EXT}. The difference is a measure of the quantity of potential energy converted in kinetic energy, and vice-versa, during each cycle, and is called "recovery" [9].

Computations have been performed by *ad-hoc* routines in Matlab R2019a (Mathworks, USA).

D. Experimental procedure (Tarantulas).

Kinematic data during free displacements of two Theraphosidae species (*Grammostola anthracina* and *Eupalaestrus weijenberghi*) were collected in previous research projects. The whole experimental protocols are described in detail in [6] and [7].

In summary, kinematic data were sampled and digitized at 50 Hz, using a whole-body model from real and virtual markers on the cephalothorax and on the main limb joints. COM_b frame-by-frame 3D positions were determined: i) using the 3D coordinates of a single marker located on the cephalothorax; and ii) determining the centre of mass and the partial mass of each body segments, and computing the COM_b using the segmental method.

E. Statistics.

The results from the two body models were compared by paired *t*-test. ANOVA was performed to compare the differences for speed and gait. The significant level was set at $\alpha = 0.05$. Statistical analyses were performed with Past 3.24 [10].

III. RESULTS

For human locomotion, a total of 5755 strides, split into walking (1627), running (1960) and skipping (2168), have been compared. They were distributed in a range of speed from 3.0 to 11.0 Kmh^{-1}. Few data were suitable for comparison in tarantulas: 15 strides in a range of speeds from 0.04 to 0.64 Kmh^{-1}.

The simplified model always resulted with an overestimation of the external mechanical work (Table I).

TABLE I
EXTERNAL WORK OVERESTIMATION WITH THE SIMPLIFIED COM MODEL.

Species	Gait	Speed (Kmh^{-1})	W_{EXT} Diff%	P (Paired *t*-test)
Tarantula (G. a.)	any	any	3.38%	0.156
Tarantula (E.w.)	any	any	33.79%	**0.010**
Human	Walking	3.0	18.13%	**< 0.001**
Human	Walking	4.0	41.96%	**< 0.001**
Human	Walking	5.0	75.59%	**< 0.001**
Human	Walking	6.5	92.34%	**< 0.001**
Human	Running	6.5	41.04%	**< 0.001**
Human	Running	9.0	50.11%	**< 0.001**
Human	Running	11.0	64.42%	**< 0.001**
Human	Skipping	6.5	26.49%	**< 0.001**
Human	Skipping	9.0	35.01%	**< 0.001**
Human	Skipping	11.0	33.61%	**< 0.001**

W_{EXT} DIFF% was computed as (W_{EXT}_SM – W_{EXT}_FM) / W_{EXT}_FM* 100.

In tarantulas, the overestimation of the external work derived from the analysis of a single marker on the cephalothorax was not statistically significant in *Grammostola anthracina* (Fig. 1). Opposite results were found in *Eupalaestrus weijenberghi*, a lighter but with relatively heavier limbs species [7].

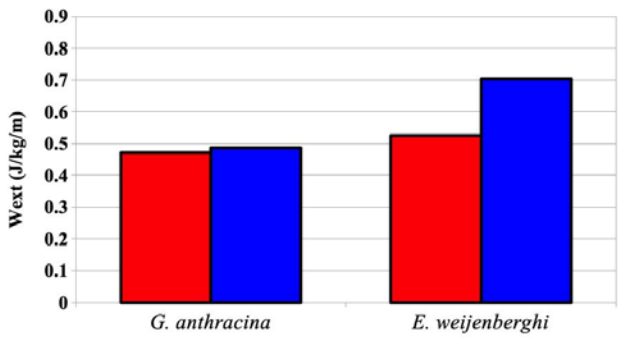

Fig. 1. External work computed from the full body model (red) versus the single marker model (blue) in tarantulas. Average values + standard deviation. Star indicates significant differences.

In human locomotion (Fig. 2) resulted clearly that the amount of the overestimation significantly increased with speed in walking and running (ANOVA: $P < 0.001$) (Table I). In skipping, only at 6.5 and 9.0 kmh^{-1} (1.8-2.5 ms^{-1}) the overestimation resulted not significantly different (ANOVA: $P < 0.001$; Bonferroni post-hoc: $P = 0.467$).

The overestimation of W_{EXT} was largely determined by differences of forward and lateral kinetic energy. In fact the W_V differences varied from -3.12% to 22.70% in walking; from 6.95% to 8.05% in running and from 5.85% to 6.49% in skipping (Table II).

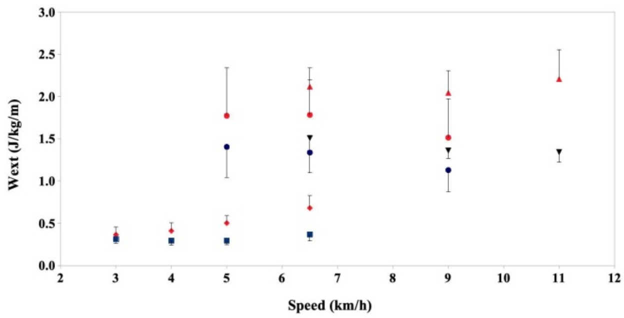

Fig. 2. External work computed from the full body model (FM) versus the simplified marker model (SM) in humans. Walking: dark squares (FM), red diamonds (SM); Running: dark triangles (FM), red triangles (SM); Skipping: dark circles (FM), red circles (SM). Average values +/- standard deviation.

TABLE II
HORIZONTAL AND VERTICAL WORK DIFFERENCES.

Gait	Speed (Kmh^{-1})	W_H Diff%	W_V Diff%
Walking	3.0	133.01%	-3.12%
Walking	4.0	122.55%	4.62%
Walking	5.0	114.51%	8.27%
Walking	6.5	97.45%	22.70%
Running	6.5	133.57%	6.95%
Running	9.0	117.55%	6.98%
Running	11.0	135.21%	8.05%
Skipping	6.5	70.19%	6.49%
Skipping	9.0	88.42%	5.85%
Skipping	11.0	89.48%	5.88%

DIFF% were computed as (W_X_SM – W_X_FM) / W_X_FM* 100.

IV. DISCUSSION

The aim of this paper was to specifically assess to what extent a simplified model can affect the estimation of the external mechanical work of locomotion in different body plans.

The external work has been investigated as a proxy of the metabolic cost of locomotion [11], because of its simpler measurement methods. However, the external work itself is an estimation of the "real" mechanical work done by the COM_b, which may vary according to different assumptions, even when computed by FD techniques [12, 13].

In humans, the ID full model (FM) we took as reference is known to return a slight overestimation of W_{EXT}, with respect to the "golden standard" FD [4]. The SM gave a further speed-dependent overestimation in walking and running, which made the results unreliable. In skipping, the bouncing asymmetrical gait, the overestimation was almost constant, in the range of 30%: still a huge drift.

The horizontal range of motion of the COM_b was more affected by the overestimation than the vertical displacements. This explain why in bouncing gaits, where the vertical components of the COM_b energies are more important [14], the differences were smaller. The great variability of walking errors were not only due to the relative magnitude of the horizontal component, but also to the phase shift between the vertical and horizontal components. Small changes of the estimated COM_b position may be amplified or reduced as effect of changes of energy recovery.

In the SM the movements of the upper and lower limb segments were not taken into account. The partial mass of human lower limbs is about 33% of the body mass, another 10% should be added for upper limbs [8]. However, part of the deviation due to the limbs movement vanishes over a cycle, due to the 50% phase shift of the limbs oscillations during walking and running. In skipping the movement is asymmetric, but the range of motion of the four limbs is reduced.

In arthropods ID is generally more difficult, due to their size and to the difficulties of identifying with markers body segments and joints. Large spiders (tarantulas) represent an exception: full body models with up to 33 markers have been employed [7]. In both the species analyzed, the SM overestimated the W_{EXT} with respect to the FM, like in humans. Despite the duplicated number of limbs, the partial limb masses of tarantulas were smaller than humans: 13% [6] and 25% [7]. In particular, the relative lighter legs of *Grammostola anthracina* may explain the small and not significant difference of W_{EXT} computed according to the two body models.

V. Conclusions

We compared the estimation of the external mechanical work from inverse dynamics, in bipedal and octopedal locomotion, using a full body model versus a simplified body model.

We found that: 1) the simplified models always resulted with an overestimation with respect to the full models; 2) the extent of the difference was speed dependent and affected particularly the estimation of the kinetic energies; 3) in bouncing and asymmetrical gaits the error could be speed-independent; 4) the error is inversely proportional to the relative weight of the main body segment (trunk or cephalothorax) with respect to the limbs.

For estimating the energy changes of the centre of mass from ID, we recommend using a full body model, which includes the limbs kinematic.

In the next future we are going to try the estimation of the kinetic and potential energies of the COM_b from accelerometers data, and compare the results with standard ID.

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