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POWER IN SPORTS: A LITERATURE REVIEW ON THE APPLICATION, ASSUMPTIONS, AND TERMINOLOGY OF MECHANICAL POWER IN SPORT RESEARCH.

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Power in Sports: a literature review on the application, assumptions, and terminology of mechanical power in sport research.

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Abstract

The quantification of mechanical power can provide valuable insight into athlete performance because it is the mechanical principle of the rate at which the athlete does work or transfers energy to complete a movement task. Estimates of power are usually limited by the capabilities of measurement systems, resulting in the use of simplified power models. This review provides a systematic overview of the studies on mechanical power in sports, discussing the application and estimation of mechanical power, the consequences of simplifications, and the terminology. The mechanical power balance consists of five parts, where joint power is equal to the sum of kinetic power, gravitational power, environmental power, and frictional power . Structuring literature based on these power components shows that simplifications in models are done on four levels, single vs multibody models, instantaneous power (IN) versus change in energy (EN), the dimensions of a model (1D, 2D, 3D), and neglecting parts of the mechanical power balance. Quantifying the consequences of simplification of power models has only been done for running, and shows differences ranging from 10% up to 250% compared to joint power models. Furthermore, inconsistency and imprecision were found in the determination of joint power, resulting from inverse dynamics methods, incorporation of translational joint powers, partitioning in negative and positive work, and power flow between segments. Most inconsistency in terminology was found in the definition and application of 'external' and 'internal' work and power. Sport research would benefit from structuring the research on mechanical power in sports and quantifying the result of simplifications in mechanical power estimations.

Glossary power terminology

work — work done by a system is the energy transferred from that system to the surrounding

energy — the quantitative property that must be transferred to an object in order to perform work on it

power — the rate of work, the amount of energy generated or transferred per unit time.

Joint power — the mechanical power generated by the human at the joints $P_j = \sum_{i=1}^{N-1} M_{i,i+1} \cdot (\omega_{i+1} - \omega_i) = \sum_{j=1}^{N-1} M_j \cdot \omega_j$

Kinetic power — the rate of change of the kinetic energy $P_k = \sum \frac{dE_{seg}}{dt} = \sum_{i=1}^{N} \frac{d}{dt}(I_i\omega_i) \cdot \omega_i + \sum_{i=1}^{N} m_i \cdot a_i \cdot v_i$

Gravitational power — the rate of change of the gravitational energy $P_G = \sum_{i=1}^{N} v_i \cdot m_i \cdot g$

Environmental power — the mechanical power from external applied forces and moments. $P_e = \sum_{i=1}^{N} \omega_i \cdot M_{e,i} + \sum_{i=1}^{N} v_i \cdot F_{e,i}$ *We here use the term environmental power to avoid the term external power which has been used to describe several different models (see section 5.2.1)*

Frictional power — the power loss from the frictional forces (e.g. air friction, roll friction) $P_f = \sum_{i=1}^{N} \omega_i \cdot M_{fr,i} + \sum_{i=1}^{N} v_i \cdot F_{fr,i}$

Mechanical power balance — the mechanical power balance consists of five parts: joint power, kinetic power, gravitational power, environmental power, and frictional power. $P_j = P_k + P_f - P_G - P_e$

Validity — the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model (Thacker, 2001)

Technique factors — variables in the movement coordination of an athlete

Mechanical power in human movement — can be determined by applying the laws of classic mechanics to the human body, and by modelling it as a linked segment model consisting of several bodies

Muscle power — the rate at which a muscle does work or transfers energy to complete a movement task

Metabolic power — metabolic work per unit time

Metabolic work — the amount of energy used by a human (during a movement task) (metabolic approach); Metabolic work can be measured by the rate of oxygen uptake, from which the energy expenditure for the complete body is estimated.

Mechanical energy expenditure — The amount of energy used by an athlete to complete a movement task based on the mechanical power balance

Single body — The human is simplified to a single mass model

Multibody — The human is modelled as a number of rigid bodies connected by idealized joints

Instantaneous power (IN) — power at any instant of time, which can be calculated using the mechanical power balance equation

Change of energy (EN) — Power, $\Delta E/\Delta t$, which is estimated by determining the change of kinetic and gravitational energy of a system ΔE over a larger time span Δt, e.g. the cycle time, and divide by Δt.

Kinematic approach — In the *kinematic approach*, only recorded kinematic data are used to estimate mechanical power.

Joint power: Single joint — joint power of an individual joint is estimated

Joint power: Multiple joints — in these researches the joint power is estimated over multiple joints

Internal power — See peripheral power

External power — See environmental power

Peripheral power — Power due to moving body segments relative to the COM (Zelik & Kuo 2012; Riddick & Kuo 2016). Only to be used when the power due to motion of the COM and due to motion of the segments relative to the COM are to be separated for measurement conveniences. Note however, that peripheral power and environmental power should not be interpreted as separate energy measures (mechanical work).

Maintenance power — the rate at which energy is used to maintain the body processes

Entropy — Represents the loss of energy to heat dissipation

Non-conservative power — Power from an irreversible process like heat dissipation, negative work, frictional work.

Conservative power — power due to conservative forces, which in principle can be re-used such as with tendon stretch

E-gross — E-gross is the ratio between the expended work (metabolic work) and the performed work (mechanical work)

Positive work — Work done by muscles to accelerate the motion.

Negative work — Work done by muscles to decelerate the motion, non-regenerative work.

1. Introduction

Mechanical power is a metric often used by sport scientists, athletes, and coaches for research and training purposes. Mechanical power is the mechanical principle of the rate at which the athlete does work or transfers energy to complete a movement task. A mechanical power balance analysis can provide valuable insight in the capability of athletes to generate power, and also in technique factors affecting the effective use of power for performance. The estimates of mechanical power are usually limited by the capabilities of motion capture systems, resulting in the necessity to use simplified power models. However, due to the introduction of these simplified models and thus variation in how power is calculated, the overview in literature in the terminology and estimation of mechanical power is disordered. Furthermore, the validity of the simplifications is often disregarded. The inconsistency in the use and definition of power came to our attention, when attempting to estimate the mechanical power balance in speed skating (Winter et al. 2016; van der Kruk 2018). Although thorough reviews exist addressing the issues of the mechanical power equations (van Ingen Schenau & Cavanagh 1990; Aleshinsky 1986) and mechanical efficiency (van Ingen Schenau & Cavanagh 1990), we found inconsistencies in the (post 1990) literature on the power estimations and terminology. Moreover, the quantification on consequences of simplifications has usually been disregarded. This not only makes the choice for a proper power model complicated, but also hampers interpretation and comparison to the literature. Providing insight into the interrelations between the different models, estimations, and assumptions can benefit the interpretation of power results and assist scientists in performing power estimations which are appropriate for their specific applications.

The aim of this study is to provide an overview of the existing papers on mechanical power in sports, discussing its application and estimation, consequences of simplifications, and terminology.

2. Method

A literature search was carried out in July 2017 in the database Scopus. The keywords "mechanical power" and "sport" were used in the search (128 articles) (*Search 1*). The search was limited to papers in English. Abstracts of the retrieved papers were read to verify whether the article was suited to the aim of the paper, papers that estimated 'power' for a sporting exercise were included (resulting in 94 articles). Three additional searches were performed in August 2017 addressing three specific power estimations, combining the keyword "sport" with "external power" (30 articles) (*Search 2*), "internal power" (4 articles) (*Search 3*), and "joint power" (35 articles) (*Search 4*), restricted to articles published after 1990. Again, the abstracts of the retrieved papers were read to verify whether the papers were suited for the current review. Papers that estimated 'power' for a sporting exercise were included (resulting in respectively 13, 3, and 26 articles).

3. Application of the term power

When the terms *mechanical power* and *sport* were used in articles, the scope of the papers can roughly be divided into two categories: the term power was either used as a *strength characteristic or performance measure* (approximately 75% of the articles), or as an indication of *mechanical energy expenditure (MEE)* (muscle work), which we focus on in this review.

The first application was mainly found in fitness and strength studies. Power is then wrongly used as a *strength measure*, attributed to a certain athlete (Winter et al. 2016). This would implicate that (peak) mechanical power is a synonym for short-term, high intensity neuromuscular performance characteristic, which is directly related to performance of an athlete. However, as Knudson (2009) also discusses, a peak power is not a fixed characteristic of a certain athlete. The power estimation in a certain exercise, e.g. the well-known vertical jump (Bosco et al. 1983), cannot be directly translated into performance of an athlete for other movements. Secondly, while strength is a force measurement, power is a combination of force and velocity (Minetti 2002); these two are not interchangeable.

Power can of course be used as an *indication of performance* during endurance sports. In cycling practices, power meters (e.g., SRM systems, Schoberer Rad Messtechnik, Welldorf, Germany) are widely accepted and used as an indication of the intensity of the training or race. Since a SRM system determines power as the product of pedal force and rotational velocity of the sprocket, under the same conditions (e.g. equal frictional and gravitational forces), the cyclist with the highest generated power per body weight over time (work) will be fastest. This is, however, not applicable for every sport. For example, power generated by a skater not only generates a forward motion (in line with the rink), but also a lateral one (perpendicular to the rink). The result of this being that the skater that generates the most power is not necessarily the fastest one finishing. Technique factors will determine the effectiveness of the generated power towards propulsion.

This review focuses on the second purpose of power estimation: as indication of *mechanical energy expenditure (MEE)*. Power is the rate of doing work, the amount of energy transferred per unit time. The relationship between mechanical power, muscle power and metabolic power is shown in Figure 1. Metabolic power can be measured by the rate of oxygen uptake, from which the energy expenditure for the complete body in time is estimated. Mechanical power can be determined by applying the laws of classic mechanics to the human body, and by modelling it as a linked segment model consisting of several bodies (Aleshinsky 1986). Both metabolic power and mechanical power estimates eventually aim to approach muscle power (either via the metabolic or via the mechanical approach). Although muscle work is closely related to the MEE for the movement, mechanical power and work are far from an exact estimation of muscle power and work and thus from MEE. The disparity between mechanical power and muscle power can, next to measurement inaccuracies, be attributed to physiological factors. In a mechanical approach, the part of the muscle power which is degraded into heat or non-conservative frictional forces inside the body or in antagonistic co-contraction is not taken into account (Figure 1). Neither is the power against conservative forces taken into account, such as tendon stretch, which in principle can be re-used (van Ingen Schenau & Cavanagh 1990).

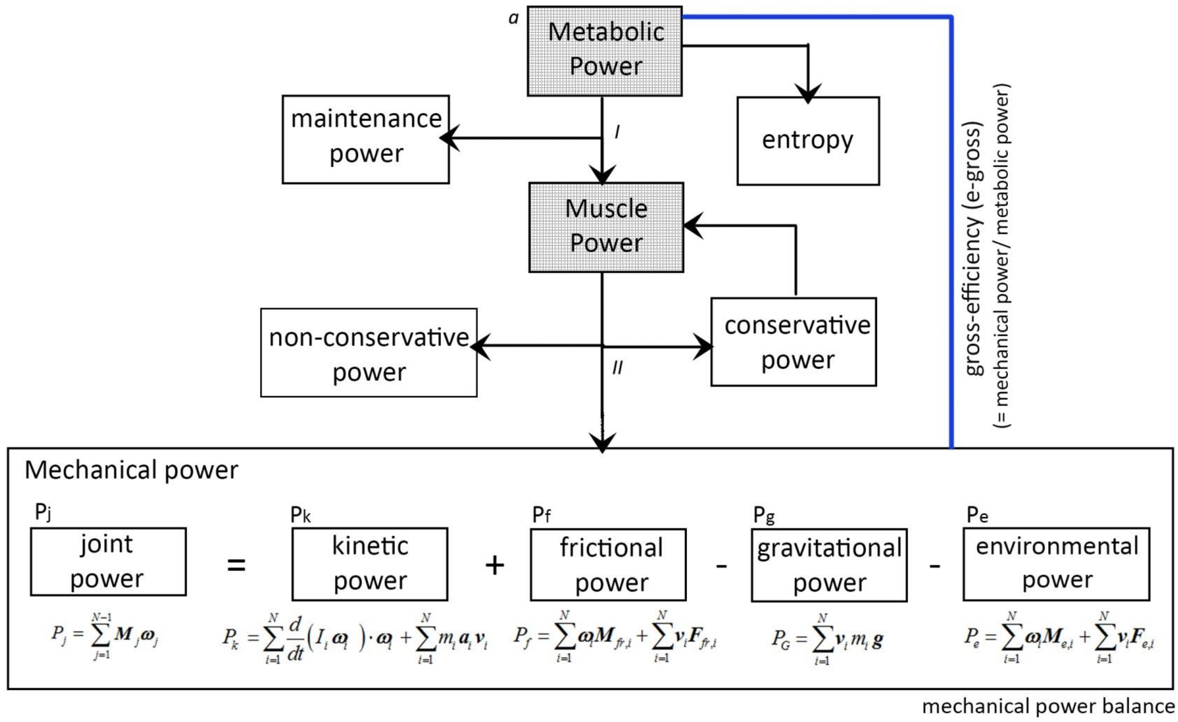


Figure 1 *The power flow in human movement. Metabolic power and work are a chemical process, estimated by for example measuring lactate or oxygen uptake (a). Energy distributes into muscle power, maintenance power and entropy. Muscle power results in mechanical power (force times contraction velocity), except for non-conservative power (e.g., power due to heat dissipation, non-conservative frictional forces inside the body, or when muscles work against each other) and conservative power (e.g. power due to conservative forces, which in principle can be re-used such as with tendon stretch). It is possible to convert the mechanical power into an actual estimation of muscle power by the use of musculoskeletal models (II). The mechanical power balance consists of joint power, which is generated by the human, which results in the kinetic power, which is the rate of change of the kinetic energy, frictional power, due to e.g. air resistance, environmental power, which is induced by external forces and moments, and gravitational power. The mechanical power can therefore be estimated by the joint power alone, or by the combination of kinetic, frictional, environmental and gravitational power. E-gross is the ratio between the expended work (metabolic work) and the performed work (mechanical work).*

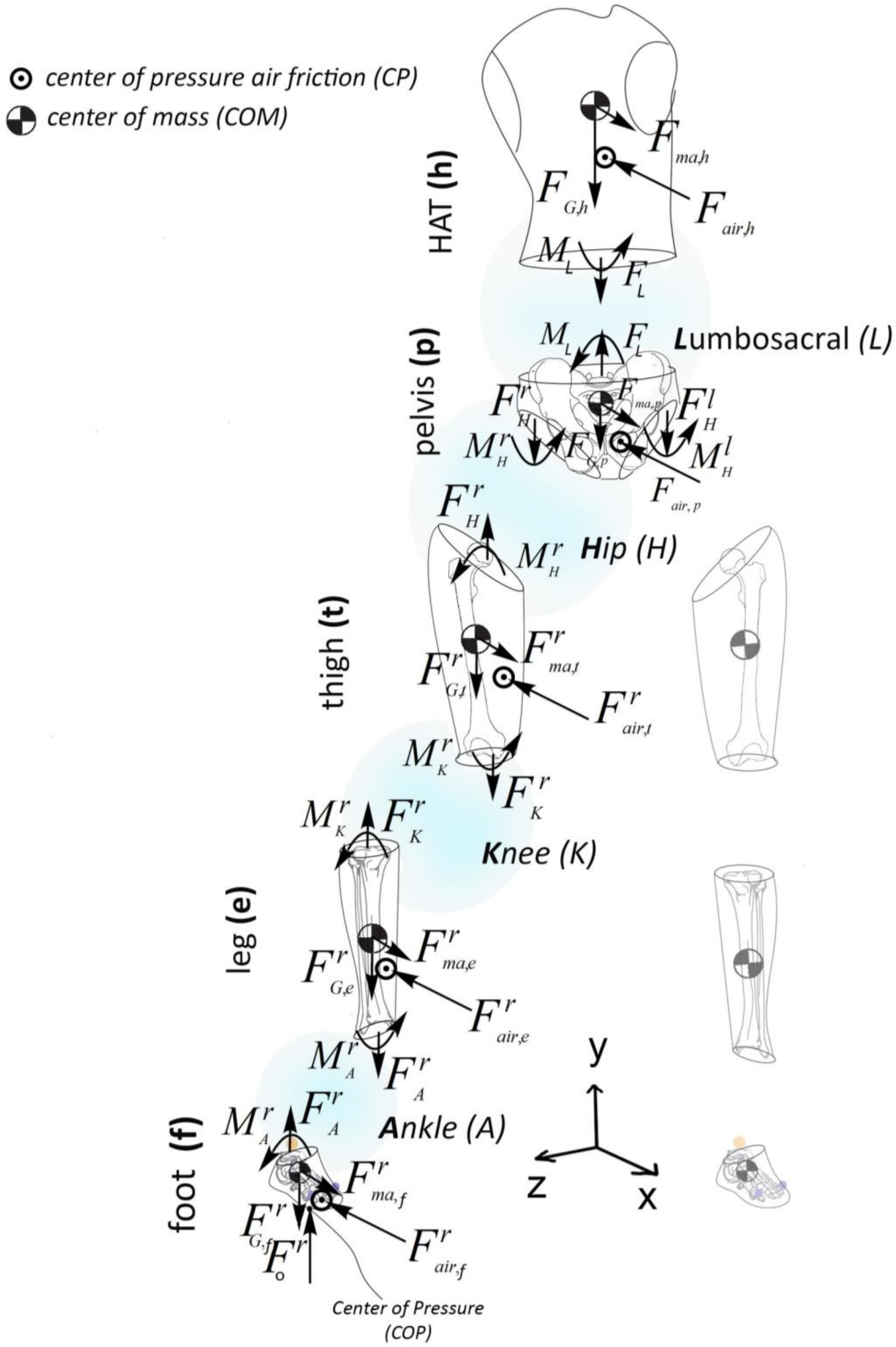


***Figure 2** Free body diagram of a rigid segment model of a human (adopted from van der Kruk et al. (2018)). The human body is here divided into eight segments; the feet (f), the legs (e), the thighs (t) , the pelvis (p) and a HAT (h), which are the head-arms-trunk. Note that HAT can only be appropriately grouped for certain sports activities (such as ones that focus on lower extremity movement). In other activities, the HAT should be taken as separate segments. The forces acting on the human are the ground reaction forces and the air frictional forces. There are joint forces and moments acting at the Ankle (A), Knee (K), Hip (H) and Lumbosecral (L) joints. Indicated are the Center of Mass (COM) of each segment, the Center of Pressure of the air friction (CP), where the air frictional force acts upon, and the Center of pressure of the ground reaction force (COP).*

4. Mechanical power equations

Before elaborating on the interpretation of mechanical power in the literature, we first set-up the complete human mechanical power balance equations (based on the work of Aleshinsky (1986) and van Ingen Schenau & Cavanagh (1990)), to expound the terminology used in this review. The equations are based on the free body diagram shown in Figure 2. The human is modelled as a chain of N linked rigid bodies (N ≥ 1), where each body is identified as a segment with index i. We start by writing down the power balance of every segment and then add them to come to the power balance for the complete system. For a better understanding of the system behaviour we distinguish between the joint power, which is the mechanical power generated by the human at the joints; the frictional power losses; the kinetic power, which is the rate of change of the kinetic energy; the gravitational power; and the environmental power, which is the mechanical power from external applied forces and moments. We here use the term environmental power to avoid confusion, since the term external power has been used to describe several different models (e.g. the change in kinetic energy of the centre of mass (COM), as well as the power measured with a power meter in cycling) (see section 5.2.1). Then, for one segment i we can determine these powers from the Newton-Euler equations of motion by multiplying them with the appropriate velocities.

Starting with the translational part, the Newton equation, we get for segment i.,

$$\left(\boldsymbol{F}_{j,i} + \boldsymbol{F}_{G,i} + F_{e,i} - \boldsymbol{F}_{f,i}\right)\cdot \boldsymbol{v}_i = m_i \cdot \boldsymbol{a}_i \cdot \boldsymbol{v}_i \qquad (1)$$

In which $\boldsymbol{F}_{j,i}$ are the joint forces, $\boldsymbol{F}_{G,i}$ are the gravitational forces, $\boldsymbol{F}_{e,i}$ are the external forces, and $\boldsymbol{F}_{f,i}$ are the frictional forces working at the segment (e.g. air friction, ice friction). $\boldsymbol{a}_i$ and $\boldsymbol{v}_i$ are respectively the linear acceleration and velocity of the segment. We write the translational power balance equation as

$$P_{j,tr,i} + P_{G,tr,i} + P_{e,tr,i} - P_{f,tr,i} = P_{k,tr,i} \qquad (2)$$

Where $P_{j,tr,i}, P_{G,tr,i}, P_{f,tr,i}, P_{e,tr,i}$ are respectively the translational joint power, the translational gravitational power, the translational frictional power, and the translational environmental power. $P_{k,tr,i}$ is the translational kinetic power.

For the rotational power we can take the Euler equation of motion, expressed in the global reference system, and multiply by the angular velocities at the segment, to come to the rotational power equation, as in

$$\left(\boldsymbol{M}_{j,i} + \boldsymbol{M}_{e,i} - \boldsymbol{M}_{f,i}\right)\cdot \boldsymbol{\omega}_i = \frac{d}{dt}\left(I_i \cdot \boldsymbol{\omega}_i\right)\cdot \boldsymbol{\omega}_i \qquad (3)$$

Where $\boldsymbol{M}_{j,i}$ are the joint moments, $\boldsymbol{M}_{e,i}$ are the external moments, $\boldsymbol{M}_{f,i}$ are the frictional moments, and $\boldsymbol{\omega}_o$ is the segment angular velocity. We write the power as

$$P_{j,ro,i} + P_{e,ro,i} - P_{f,ro,i} = P_{k,ro,i} \qquad (4)$$

Next, we add up the rotational and translational segment powers of all segments. The constraint forces in the joints have no contribution to the total power equation, since only relative rotation at the joint between the two segments is assumed (linked segment model), and therefore will drop out of the equation. Joint forces can redistribute energy between segments and links, but not add energy to the total body system (Aleshinsky 1986). Note however, that if an applied inverse kinematics method allows for translations in the joint, as in Ojeda et al. (2016), or a six degree of freedom joint is applied (e.g., as is possible in biomechanical modelling software such as OpenSim (Delp et al. 2007) and Visual3D (C-Motion,Germantown,MD, USA)), joint forces do play a role and the constraint forces should be accounted for in the power determination (see section 5.1.3).

The total power equations for the system, now written in terms of joint power, kinetic power, frictional power, gravitational power, and environmental power are,

$$P_j = P_k + P_f - P_G - P_e \tag{5}$$

In which we have the joint power (P_j) which is directly calculated using the moments at the joint (M_j) and the rotational velocities around the joint (ω_j), as in

$$P_j = \sum_{i=1}^{N-1} \boldsymbol{M}_{i,i+1} \cdot (\boldsymbol{\omega}_{i+1} - \boldsymbol{\omega}_i) = \sum_{j=1}^{N-1} \boldsymbol{M}_j \cdot \boldsymbol{\omega}_j \tag{6}$$

We find the gravitational power in equation 5, as in

$$P_G = \sum_{i=1}^{N} \boldsymbol{v}_i \cdot m_i \cdot \boldsymbol{g} \tag{7}$$

And the frictional power, which consists of translational power and rotational power,

$$P_f = \sum_{i=1}^{N} \boldsymbol{\omega}_i \cdot \boldsymbol{M}_{fr,i} + \sum_{i=1}^{N} \boldsymbol{v}_i \cdot \boldsymbol{F}_{fr,i} \tag{8}$$

And the environmental power, which consists of translational power and rotational power,

$$P_e = \sum_{i=1}^{N} \boldsymbol{\omega}_i \cdot \boldsymbol{M}_{e,i} + \sum_{i=1}^{N} \boldsymbol{v}_i \cdot \boldsymbol{F}_{e,i} \tag{9}$$

And the change of kinetic energy in the segments,

$$P_k = \sum \frac{dE_{seg}}{dt} = \sum_{i=1}^{N} \frac{d}{dt}\left(I_i \boldsymbol{\omega}_i\right) \cdot \boldsymbol{\omega}_i + \sum_{i=1}^{N} m_i \cdot \boldsymbol{a}_i \cdot \boldsymbol{v}_i \tag{10}$$

In summary, the mechanical power balance consists of five parts, joint power, kinetic power, gravitational power, environmental power and frictional power. Joint power is generated by the human, and is the result of muscle power. This entails that for the most complete estimation of mechanical (human) power either the joint power should be determined directly through measurements of joint torques and angular velocity, or indirectly via the sum of frictional, kinetic, environmental and gravitational power, $P_f, P_k, P_e,$ and P_G (Figure 1). Usually, these powers are approximated depending on the available recording methods, and therefore sometimes not all terms in the mechanical power balance are estimated resulting in a simplified model.

Instantaneous power (IN) versus change of energy (EN)

Power is the amount of energy per unit of time. In the literature there are, apart from the different models, two different approaches to estimate power. First, what is referred to as instantaneous power (IN). Instantaneous power is power at any instant of time, which can be calculated using the power balance equation presented earlier (van Ingen Schenau & Cavanagh 1990). The second approach is by determining the change of kinetic and gravitational energy of a system (EN) over a larger time span, e.g. the cycle time, and divide this energy over the larger Δt. We know that the kinetic energy at time t is:

$$E_{k,i,t} = \frac{1}{2} m \cdot \mathbf{v}_{i,t}{}^{T} \cdot \mathbf{v}_{i,t} + \frac{1}{2} \boldsymbol{\omega}_{i,t}{}^{T} \cdot I_{i,t} \cdot \boldsymbol{\omega}_{i,t} \tag{11}$$

And the gravitational energy at time t:

$$E_{g,i,t} = m \cdot g \cdot y_{i,t} \tag{12}$$

Note that EN only estimates average mechanical power, and does not give insight into the power development, or peak powers. Also, oscillatory movements will result in a zero outcome with EN (e.g. walking).

5. Power models in the literature

Based on the mechanical power equations, we sorted the literature of *Search 1-3* concerning the estimation of mechanical power as an indication of mechanical energy expenditure in Tables 1 & 2. For each study the power model (P_j, P_k, P_f, P_g, P_e), the estimation approach (IN, EN) and the dimensions (1D, 2D, 3D) are indicated. Results show that simplifications are done on three scales: the number of bodies (single body vs multibody), the recorded data (kinematic versus kinetic data), and the time interval (IN versus EN). The analysis on results for the literature of *Search 4*, are given separately in Table 3, divided into articles for single joints versus multi-joints, and work versus power results.

5.1 Simplifications of power models

5.1.1 Single body models

When an athlete is simplified to a single mass, the assumption is that this mass is located at the COM of the full body. Constructing the mechanical power balance (eq. 5) for this single body system results in an equation with one body left, the COM, which automatically neglects any relative motions between the segments and the COM, and any power related to these motions. Although this single body approach is used often (27 papers, see Table 1), estimation of the impact of this simplification has only been performed in two studies, both on running (Arampatzis et al. 2000; Martin et al. 1993).

Arampatzis et al. (2000) (see also Table 1) compared four mechanical power models in over-ground running at velocities ranging from 2.5-6.5 m/s. Their results showed that the mean mechanical power estimated with the single body model, based on the change in potential and kinetic energy, is 32% higher than the power of the 2D joint power estimation at 3.5m/s running speed. Martin et al. (1993) determined the mechanical power in treadmill running with three methods (see Table 1). Based on their results, a single body kinematic approach resulted in a 47% lower mechanical power estimation compared to joint power, running at 3.35 m/s. Since the neglected frictional power (air friction) at these running speeds is relatively small (<1% of joint power, based on Tam et al. (2012)), the difference between joint power estimation and the kinematic approach for the single body estimation is attributed to the neglected relative motions of the segments to the COM and the fact

Table 1
Structuring of the literature for single body models Indicated are the terminology, the power estimation, the dimensions of the model (1D, 2D, 3D) and whether the power is estimated instantaneously (Instantaneous power (IN)) or via the change in energy over a time span (EN). Inconsistent terminology and oversimplifications are indicated in the final column.

Article	Terminology	Dimensions	P_j	P_k TRANS	P_k ROT	P_f	P_g	P_e	IN/ EN	Comments	Applicable topics from this review
Single Body models											
Running											
Yanagiya et al. (2003)	Mechanical power	1						X	IN	velocity of the belt times the horizontal force on the handle bar	Directional power (see 5.2.2)
Fukunaga et al. (1981) (sprint)	Forward power	2						X	IN		
Pantoja et al. (2016) (sprint)	Mechanical power	1		X		X			IN		
di Prampero et al. (2014) (sprint)	Mechanical accelerating power	1		X			X		IN		
Minetti et al. (2011) (skyscraper)	External power (internal power)	1					X		EN	Regression for internal power	Internal and external work (see 5.2.1)
Gaudino et al. (2013) (soccer)	Mechanical power	1		X					EN		Directional power (see 5.2.2)
Arampatzis et al. (2000)	Mechanical power	2						X	IN	+14% mean mechanical power[a] [compared to joint power in same experiment, Table 2]	Oversimplified model (see 5.1.1)
		2		X			X		EN	+32% mean mechanical power[b] [compared to joint power in same experiment, Table 2]	
Martin et al. (1993)	COM kinematics approach	2		X			X		EN	−47% mean mechanical power[c] [compared to joint power in same experiment, Table 2]	
Bezodis et al. (2015)	External power	1		X					EN		
Cycling											
Telli et al. (2017)	External power							X	IN		Internal and external work (see 5.2.1)
	Additional External power	3		X			X		EN		Internal and external power (see 5.2.1)
Van Ingen Schenau et al. (1992)	External power	1		X		X			EN		
Swimming											
Seifert et al. (2010)	External power, Relative power, absolute power	1				X			IN	*Fdrag measured:* the swimmers swam on the MAD-system, which allowed them to push off from fixed pads with each stroke These push-off pads were attached to a rod which was connected to a force transducer, enabling direct measurement of push-off forces for each stroke. Assuming a constant mean swimming speed, the mean propelling force equals the mean drag force.	
Toussaint and Truijens (2005)		1		X		X			–	Theoretical, not measured	
Toussaint and Beek (1992)		1		X		X			–	Theoretical, not measured	
Rowing											
Hofmijster et al. (2008)	External power	1						X	IN		
Buckeridge et al. (2012)	External power	1						X	IN	Integral of handle displacement-handle force curve divided by time.	
Hofmijster et al. (2009)	Internal Power	1		X							Internal and external power (see 5.2.1)
Colloud et al. (2006)	External mechanical power							X	IN	Fhandle*vhandle-Fstretcher*vstrechter	
Speed skating											
Houdijk et al. (2000a,b)	External power	1				X			EN	About 20% of the joint power consists of Pk + Pg based on van der Kruk et al. (2018)	
de Koning et al. (2005)	Power output	1		X		X			EN		
de Koning et al. (1992) (sprint)	External Power	1		X		X			EN		

Wheelchair								
Mason et al. (2011)	External Power Output	1		X		EN	*Fdrag measured:* The drag test setup consisted of a strain gauge force transducer, attached at the front of the treadmill to the front of the wheelchair. Participants were instructed to remain stationary while the treadmill was raised over a series of gradients at a constant velocity	
Veeger et al. (1991)	External power	1		X		EN	*Fdrag measured:* A cable was connected between the wheelchair (standing immobile on a sloped treadmill) and a force transducer mounted upon a frame at the front of the treadmill. Fdrag equalled the force needed to prevent the wheelchair from moving backward under influence of belt speed and slope effects.	
Kayaking								
Jackson (1995)		1	X	X		EN	Theoretical, not measured	
Nakamura et al. (2004)	Internal power						Regression function	Internal and external work (see 5.2.1)
Sideway locomotion								
Yamashita et al. (2017)	External power, vertical power, horizontal power, lateral power	2			X	IN		Internal and external work (see 5.2.1) Directional power (see 5.2.2)
Bench press								
Jandacka and Uchytil (2011) (soccer)		1			X	IN	Vertical velocity of the COM x ground reaction force of the bench to the floor	Oversimplified model (see 5.1.1)

[a] Based on mean mechanical power of Table 2 at 3.5 m/s in A. Arampatzis et al. (2000): ((Method 1- Method 4)/Method 4) * 100%.
[b] Based on mean mechanical power of Table 2 at 3.5 m/s in A. Arampatzis et al. (2000): ((Method 2- Method 4)/Method 4) * 100%.
[c] Based on Martin et al. (1993): (($\dot{W}_{EXCH}$ in Table 2-TMP in Table 4)/(TMP in Table 4))) * 100%.

Table 2
Structuring of the literature for multi body models. Indicated are the terminology, the power estimation, the dimensions of the model (1D, 2D, 3D) and whether the power is estimated directly (Instantaneous power (IN)) or via the change in energy over a time span (EN). Applicable topics from this review are indicated in the last column.

Article	Terminology	Dimensions	P_j	$P_{k\ TRANS}$	$P_{k\ ROT}$	P_f	P_g	P_e	IN /EN	Comments	Applicable topics from this review
Multibody models											
Running											
Willwacher et al. (2013)	Joint power	3	X								
Arampatzis et al. (2000)	Joint power	2	X						IN	15 segments	
	Mechanical power	2		X	X		X		EN	+10% difference in mean mechanical power[a] [compared to joint power in same experiment] 15 segments	
Martin et al. (1993) (sprint)	Joint power	2	X						IN	14 segments	
	Segments kinematics approach	2		X	X		X		EN	-56% mean mechanical power[b] [compared to joint power in same experiment] 14 segments	
Cycling											
De Groot et al. (1994)	Joint power		X							theoretical	
Neptune and Van Den Bogert (1997)	Joint power	2	X						IN		
	Internal and external power	2		X	X	X	X		IN		Internal and external work (see 5.2.1)
Telli et al. (2017)	Internal power	3		X	X				EN	Relative to COM	Internal and external work (see 5.2.1)
Golf											
McNally et al. (2014)	Joint power	3	X								
Walking											
Royer and Martin (2005)	Mechanical work	2		X	X		X		EN		

[a] Based on mean mechanical power of Table 2 at 3.5 m/s in A. Arampatzis et al. (2000): (Method 3-Method 4/Method 4) * 100%.
[b] Based on Martin et al. (1993): (($\dot{W}_{WB}$in Table 3-TMP in Table 4)/(TMP in Table 4))) * 100%.

Table 3
Articles found with the search terms joint power and sport. The literature was divided into estimating power or work of a single joint (the research estimated the joint power of individual joints), and power and work of multiple joints (joint power was taken over multiple joints). Noted are the applied inverse dynamics technique with reference (N.M. = not mentioned). For the work estimation, the conversion from power to work is given and whether positive and negative work are separated. Articles are sorted on year of publication.

Joint power					
Power per joint	Movement	Inverse dynamics method			
Paquette et al. (2017)	Running	"Newtonian inverse dynamics"	**N.M.**		
Middleton et al. (2016)	Cricket	"Standard inverse dynamics analysis"	**N.M.**		
Barratt et al. (2016)	Cycling	Inverse dynamics method	Elftman (1939)		
Pauli et al. (2016)	Squats, jumps	**N.M.**	**N.M.**		
Van Lieshout et al. (2014)	Exercises	**N.M.**	**N.M.**		
Creveaux et al. (2013)	Tennis	[Method is fully described in paper]	n.a.		
Kuntze et al. (2010)	Badminton	**N.M.**	**N.M.**		
Riley et al. (2008)	Running	"Vicon plug-in-gait"	Vicon		
Dumas and Cheze (2008)	Gait	"Inverse dynamics based on wrenches and quaternions"	Dumas et al. (2004)		
Vanrenterghem et al. (2008)	Jumping	**N.M.**	**N.M.**		
Schwameder et al. (2005)	Walking	"Standard 2D inverse dynamics routine"	**N.M.**		
Rodacki and Fowler (2001)	Exercise	"Newtonian equations of motion"	**N.M.**		
Jacobs and van Ingen Schenau (1992)	Sprint	"Linked segment model"	Elftman (1939)		
Energy per Joint	Movement	Inverse dynamics method		Power to work	Absolute
Schache et al. (2011)	Running	"A standard inverse dynamics technique"	Winter (2009)	integral of joint power over time	Not absolute (pos and neg work)
Hamill et al. (2014)	Running	"Newton-Euler inverse dynamics approach"	**N.M.**	**N.M.**	Not absolute (pos and neg work)
Sorenson et al. (2010)	Jump	Inverse Dynamics	Visual 3d	Integral of joint power over time	Not absolute (pos and neg work)
Yeow et al. (2010; Yeow et al. 2009)	Landing jump	**N.M.**	**N.M.**	Integral of joint power over time	Not absolute (pos and neg work)
Power multiple joints	Movement	Inverse dynamics method			
Strutzenberger et al. (2014)	Cycling	"Sagittal plane inverse dynamics"	Visual 3D	Integral of the summed ankle, knee, and hip powers	–
Energy multiple joints	Movement	Inverse dynamics method		Power to work	Absolute
Greene et al. (2013, 2009)	Rowing	Custom program	Winter (2009)	Sum of the joint mechanical energy	**N.M.**
Attenborough et al. (2012)	Rowing	Inverse dynamics	Winter (2009)	Integration of the absolute value of the power time series curve for each joint	Absolute per joint
Lees et al. (2006)	Jumping	"Inverse dynamics using standard procedures"	Miller and Nelson (1973), Winter (2009)	Time integral per joint "Standard procedure', de Koning and van Ingen Schenau (1994); sum of left and right limb;	Not absolute (pos and neg work)
Devita et al. (1992)	Running	"An inverse dynamics method"	**N.M.**	Resultant joint powers around hip, knee and ankle joint were summed at each time point.	Not absolute (pos and neg work)

that only measured kinematic data were used in the single body, which is expected to be less accurate than the combination of measured force and kinematic data. The difference in results between the two studies is surprising, since the mechanical equations, running speeds, and joint power models (14 versus 15 segments, 2D, absolute per joint) are similar for both studies, while the only difference was the treadmill versus over-ground condition. Unfortunately, Arampatzis et al. (2000) do not discuss this difference.

It is clear that, although there is no consensus on whether a single body model under- or overestimates the mechanical power in running (see also section 5.2.1), both studies show significant differences between a single body model and a joint power model. Since this is the consequence of disregarding the motions of the segments and kinematic measurement accuracy, validity will likely be different for different movements.

Three studies were found that determined the mechanical power in locomotion with a single body model by multiplication of an environmental force (e.g. the measured ground reaction forces) times the velocity of the centre of mass of the complete body (Arampatzis et al. 2000; Yamashita et al. 2017; Jandacka & Uchytil 2011). Theory of this model lays in the simplification of an athlete to one rigid body being propelled by a force. Therefore, the ground reaction force, which acts on the foot is now shifted to the COM and assumed to cause the movement of the complete (rigid) body. However, although a force can be replaced by a resultant force acting at the COM without changing the motion of the system, the work of the system will divert from the actual work. For example, the ground reaction force in running, acting on the foot, in principle hardly generates power, after all the foot has close to zero velocity (Zelik et al. 2015). By assuming that the force acts on the COM of the athlete, the force suddenly generates all power (and therefore work). So although mechanically, with the rigid body assumption, the simplified model is in balance, the validity of modelling an athlete as a point mass (single body) driven by the ground reaction force is highly doubtful. The results of such a model should in no case be interpreted as an indication of muscle power/work or MEE, since the relationship with actual joint power is lost by the oversimplification of an athlete.

For single body power estimations, both IN approaches (e.g. Pantoja et al. 2016; di Prampero et al. 2014; Seifert et al. 2010) and EN approaches (e.g. Minetti et al. 2011; Gaudino et al. 2013; Houdijk et al. 2000) were found. An EN approach results in an average mechanical power estimate. Consequently, there is no insight into the course of power during the motion cycle, e.g. peak power. Also, oscillatory motions are averaged such that positive and negative power would negate each other, which are tricky assumptions for several sports like running, cycling, swimming, etc. Van der Kruk (2018) found that the kinetic and gravitational power related to these oscillatory motions in speed skating (zig-zag motion of the skater over the straight), appeared to account for almost 20% of the joint power. Therefore, assumptions on ignoring velocity fluctuations, or motions that do not directly contribute in the forward motion, should be well validated. Especially when working with top-athletes or highly technical sports, these components could be the key-factors in an athlete's performance, therefore IN models seem more appropriate than EN models for understanding performance (Caldwell & Forrester 1992).

5.1.2 Multibody models

Using a multi-body approach is much more complex than the single body approach, since the motion of the separate body parts needs to be measured. The benefit of this approach is that the power per segment gives insight into the distribution of power over the body. In the *kinematic approach*, only recorded kinematic data are used to indirectly estimate mechanical power: frictional power, kinetic power and gravitational power (P_f, P_k and P_G). The main difference with the joint power estimation, is the absence of measured force data. Furthermore, in the kinematic approach frictional power is neglected in running and walking studies, and gravitational power in cycling studies.

The studies by Arampatzis et al. (2000) and Martin et al. (1993), which were mentioned earlier, enable the comparison of a kinematic multi-body approach, which resulted in respectively 10% more mechanical power and 56% less mechanical power when compared to the joint power estimation (at respectively 3.5 m/s and 3.35 m/s) (Table 2). Again, their results are contradictory and largely diverge in magnitude. However, the results do stress the need of accurate kinematic measurements in the models. The approaches in which both recorded kinematic and force data were used to estimate MEE correlated better with the aerobic demand of the athletes than the kinematic data only approaches (Martin et al. 1993).

5.1.3 Joint power

Since we found several inconsistencies in estimating joint power in the articles of *Search 1-3* (see Table 2), we performed a specific search for joint power (*Search 4*). Analysis of these studies lets us identify two classes of differences in joint power estimation: the inverse dynamics method (including the degrees of freedom of the joints) and the estimation of power to work (see Table 3).

Joint power estimation requires the determination of joint moments and forces via *an inverse dynamics method*. Although several methods exist to estimate joint moments (e.g. Dumas et al. 2004; Kuo 1998; Elftman 1939), the bottom-up approach (Winter 2009; Elftman 1939; Miller & Nelson 1973) is still the most applied method, and referred to as the 'standard inverse dynamics method' or 'Newton(-Euler) inverse dynamics approach' without citing further reference. However, since the bottom-up approach can leave large residuals at the trunk and the joint power is largely influenced by the inverse dynamics method (up to 31% (van der Kruk 2018)), there should be more attention towards this part of the power estimation.

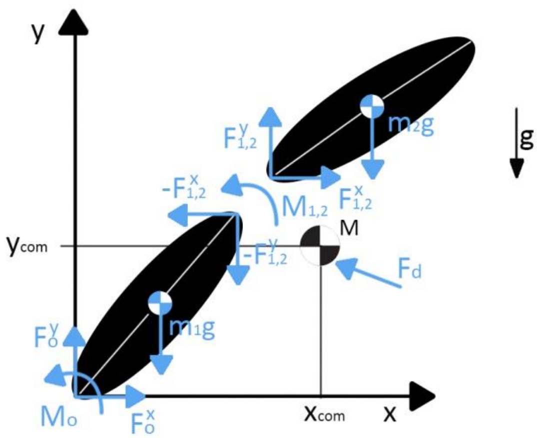
Underlying the inverse dynamics is the choice for the kinematic model, where we mainly found differences in the *degrees of freedom of the joint* (van der Kruk et al. 2018). If translation is allowed in the joints, the joint forces suddenly generate power (see eq. 2). Application of 6 DOF joints, and therefore incorporation of translational joint power is becoming more common, due to the ever more detailed 3D human joint models (e.g. OpenSim, Visual3D). The effect of these forces on the joint power, and whether the translations are not part of residuals of the choice in inverse kinematics method, rather than a physiological phenomenon, falls outside of the scope of this review (Ojeda et al. 2016; Zelik et al. 2015). However, we want to make the reader aware that differences do occur and thereby influence the joint power estimations, where the increase in complexity will not automatically imply improvement.

The second class of difference was found in the integration of joint *power to work* (as indication of MEE). For the power in a single joint, a separation is made between *negative and positive power*. Negative power occurs when the moment around the joint is opposite to the angular velocity of the joint, which would denote braking (dissipation of energy). With only mono-articular muscles, this would imply the production of eccentric power. However, bi-articular muscles can 'transfer' power to adjacent joints. Converting power into work is done by taking the integral of the power curve over time. In the literature, the division is made between *positive work* and *negative work* (Schache et al. 2011; Yeow et al. 2009; Hamill et al. 2014; Sorenson et al. 2010). This division is made since, from a biomechanical perspective, it is assumed that for negative muscle work (or eccentric muscle contraction) the metabolic cost is lower than for positive muscle power requiring concentric muscle contraction. However, there is no general consensus on the exact magnitude of this difference. Caldwell & Forrester (1992) even argue that the division into positive and negative work should be rejected, since mechanical power is an indication of muscle power, not metabolic cost and thus 1 J of negative power reflects 1 J of positive power. However, currently the general consensus is to separate negative from positive work; musculoskeletal simulations might shed light on the difference in magnitude in the future.

For power estimation in multiple joints, the estimation of mechanical work (indication of MEE) becomes more complicated due to the *power flow* between segments (and thus joints); bi-articular muscles activations can induce both negative and positive power simultaneously around adjacent joints (Van Ingen Schenau & Cavanagh 1990). When no power flow is assumed, the integral of the absolute joint power per joint is taken and summed over the joints (Attenborough et al. 2012). If power flow is assumed, the joint powers are first summed over the joints and then the integral over time is taken, again allowing for the separation of negative and positive power (Lees et al. 2006; Devita et al. 1992). What the best approach is, has yet to be determined. Hansen (2003) found in cycling that the MEE was most accurately measured with a model that allowed for energy transfer only between segments of the same limb. Articles that do not report the method for MEE estimation are inappropriate for comparison (e.g. Greene et al. 2013), since the difference between the two methods can go up to >2.5x the MEE (measured in running (Martin et al. 1993). Note that this power flow issue not only accounts for the estimation of joint power over several joints, but also for power transfer between segments in other kinematic multi-body models (Willems et al. 1995).

[Table 3]

5.2 Inconsistent terminology



M	Mass of the system
y_{com} , x_{com}	Coordinates of the COM of the system
g	Gravitational acceleration
m_i	Mass of the i-th link
com	Center of mass of the system
ci	Center of mass of the i-th link
I_{ci}	Moment of inertia at the center of gravity of the i-th link
ϕ_i	Angular position of the longitudinal axis of the i-th link with respect to the axis ox
$y_{A/B}$, $x_{A/B}$	Correspond to $x_A - x_B$ and $y_A - y_B$
$F^x_{i-1,i}$, $F^y_{i-1,i}$	Components of the (i-1)th and the i-th links' resultant joint force applied to the i-th link
F^x_o , F^x_d , F^y_o , F^y_d	Components of the resultants of the external forces applied to the i-th link
M_o , M_d	Moments of the external forces acting about the ends of the terminal links
$M_{i-1,i}$	Control moment acting about (i-1)-th and i-th links joint

Figure 3 *Free body diagram of a two-link segment body*

5.2.1 Internal and external work

The terms internal and external power and work are often used. However, these terms are ill-defined, terminology is inconsistent, and the actual purpose of separation is dubious. We will discuss these issues by considering a simple 2D two-link model (Figure 3). The mechanical power equations of this simple model can be divided into external powers and internal powers. We here employ the definition of internal power as the energy changes of the segments, relative to the COM of the complete body (Aleshinsky 1986). The power equation for this model can be divided as follows:

$$\frac{dE}{dt} = \frac{d}{dt}\left\{\frac{M\cdot\left(\dot{x}_{com}^2+\dot{y}_{com}^2\right)}{2} + M\cdot g\cdot y_{com}\right\} + \frac{d}{dt}\left\{\sum_{i=1}^{N}\left[\frac{m_i\cdot\left(\dot{x}_{ci/com}^2+\dot{y}_{ci/com}^2\right)}{2}+\frac{I_{ci}\cdot\dot{\phi}_i}{2}\right]\right\} = F_o^x\cdot\dot{x}_{com} - F_d^x\cdot\dot{x}_{com} + F_o^y\cdot\dot{y}_{com} - F_d^y\cdot\dot{y}_{com} + F_o^x\cdot\dot{x}_{o/com}+F_o^y\cdot\dot{y}_{o/com} + \left[\sum_{i=1}^{N-1} M_{1,2}\cdot\left(\dot{\phi}_2-\dot{\phi}_1\right)\right] + M_o\cdot\dot{\phi}_1 \quad (13)$$

in which the parts in the blue boxes represent the external powers, and the parts in the green boxes the internal powers. Note that the external force F_o acts at o, and:

$$\dot{x}_o = \dot{x}_{com} + \dot{x}_{o/com};\ \dot{y}_o = \dot{y}_{com} + \dot{y}_{o/com} \quad (14)$$

Although these equations show that the system energy can be presented as a sum of external and internal power, the mechanical work is *not equal* to the sum of the 'internal' and 'external' work (Zatsiorsky 1998; Aleshinsky 1986). Take into consideration that:

$$\dot{x}_{com} = \dot{x}_o - \dot{x}_{o/com};\ \dot{y}_{com} = \dot{y}_o - \dot{y}_{o/com} \quad (15)$$

If we then determine mechanical work by taking the absolute integral of the power equations separated into internal and external power, we obtain:

$$\int_{T1}^{T2}\left|\frac{d}{dt}\left\{\frac{M\cdot\left(\dot{x}_{com}^2+\dot{y}_{com}^2\right)}{2}+M\cdot g\cdot y_{com}\right\}\right|dt + \int_{T1}^{T2}\left|\frac{d}{dt}\left\{\sum_{i=1}^{N}\left[\frac{m_i\cdot\left(\dot{x}_{ci/com}^2+\dot{y}_{ci/com}^2\right)}{2}+\frac{I_{ci}\cdot\dot{\phi}_i}{2}\right]\right\}\right|dt \neq$$

$$\int_{T1}^{T2}\left|F_o^x\cdot\dot{x}_o - F_d^x\cdot\dot{x}_{com} + F_o^y\cdot\dot{y}_o - F_d^y\cdot\dot{y}_{com} - F_o^x\cdot\dot{x}_{o/com} - F_o^y\cdot\dot{y}_{o/com}\right|dt +$$

$$\int_{T1}^{T2}\left|F_o^x\cdot\dot{x}_{o/com}+F_o^y\cdot\dot{y}_{o/com}+\left[\sum_{i=1}^{N-1}M_{1,2}\cdot\left(\dot{\phi}_2-\dot{\phi}_1\right)\right]+M_o\cdot\dot{\phi}_1\right|dt$$

(16)

As mentioned by Aleshinsky in 1986, there are external forces (F_o) inside the 'internal' work, therefore the internal and external work are not independent measures. Moreover, the absolute values (due to positive and negative work) destroy the balance. Members of the expressions in the internal and external work are powers which regularly fluctuate out of phase, thereby cancelling each other out. By treating them as independent measures, the work doubles instead of cancelling out, while in reality these powers do not cost any mechanical energy (e.g. pendulum motion). Replacing an actual system of forces applied to a body by the resultant force and couple does not change the body motion. It can change, however, the estimation of performed work. Therefore, the power of the external forces as a hypothetical drag force, when assumed this acts at the COM, can be seen separate from the internal power (there is no relative velocity between the point of application of the force and the COM). However, ground reaction forces, or any other forces with a point of application different from the COM will be part of both the 'internal' and 'external' work, and therefore are not independent measures (see also section 5.1.1). Despite the mechanical incorrectness of the separation of internal from external work, and the discussion involving these measures (Zatsiorsky 1998; van Ingen Schenau 1998), more recent publications still make this distinction (e.g. Minetti et al. 2011; Nakamura et al. 2004), raising the question what the benefit is of separating the mechanical energy into internal and external energies if the separation is mechanically incorrect? In cases where the whole mechanical power balance is estimated, there seems no point in dividing the power into internal and external power or work. This

separation has not given additional useful insight into human power performance in sports so far. The only application of the separation could be when a single body model is used and therefore only external power can be measured. The balance ratio between internal and external power can then be used to provide insight into the consequences of the simplification.
Adding to the confusion of the interpretation of external and internal power, is the inconsistent use of the terms. The use of the term 'internal' is logically diffuse, while it might refer to muscular or metabolic work (Williams 1985). In this literature review, two articles were found that used the internal power for estimations different from the definition given above, defining internal mechanical power loss as the part of power absorbed by the muscles that is lost to heat (estimated as fluctuations in kinetic energy of the back and forth moving of the rower on an ergometer) (Hofmijster et al. 2009), or the total energy required to move segments (Neptune & Van Den Bogert 1997). However, more models and interpretations of internal power have been published, that all largely (up to 3x) differ in power output estimation (Hansen et al. 2004).
Also the term external power is inconsistently used. Aleshinsky (1986) defined the term as the change in energy of the COM of the athlete, and can therefore be seen as a single body model. The origin of the term lies in the assumption that the human generates power only to overcome external forces (e.g. air friction, ground friction). In speed skating (Houdijk et al. 2000; de Koning et al. 1992), wheelchair sports (Veeger et al. 1991; Mason et al. 2011) and swimming (Seifert et al. 2010), the term external power is used for the estimation of frictional power (P_f), assuming that, under constant velocity, this is equal to the power generated by the human. In rowing (Hofmijster et al. 2008; Buckeridge et al. 2012; Colloud et al. 2006) and cycling (Telli et al. 2017), where ergometers are available, the term external power is used to describe the power output measured by the ergometer, what we define as environmental power (P_e). Note however, that the power output measured with an ergometer or a system such as SRM is not necessarily the same as the COM movement. If a cyclist stops pedalling on an ergometer but moves her or his upper body up and down, there is a COM movement (due to joint power), but there is no power measured at the ergometer (P_e) (the cyclist of course does not have to stop pedalling for the same effect). In running and walking, where the frictional power is only marginal and environmental power in principle is zero, the term external power is used to describe the change in kinetic energy (P_k) (Bezodis et al. 2015) and/or gravitational energy (P_g) (Minetti et al. 2011) of the COM, but also for an estimation done by multiplication of the ground reaction forces times the COM velocity (see section 5.1.1 on the reliability of this model). More interpretations of external power can be found in Table 1.
So even though the term external power is well known and frequently used, the estimation is not straightforward and interrelations are not always clear. The terms internal and external power can, however, be structuralized and classified by the mechanical power balance from section 3, as was done in Table 1 and 2. We propose a standard in section 6.

5.2.2 Directional power

In the studies on running and walking, we found many power terms related to some sort of direction: forward power, lateral power, etc. (see Table 1 and 2). Since power is a scalar, it is in principle incorrect to give the power a certain direction, although of course the forces and velocities related to power have a direction. The separation of the mechanical power equations into these different directions is actually not beneficial. Take for example a situation where there is no environmental power acting on the human e.g. walking; in that situation the power equation simplifies to:

$$\frac{d}{dt}\left\{\frac{M\cdot\left(\dot{x}_{com}^2+\dot{y}_{com}^2\right)}{2}+M\cdot g\cdot y_{com}\right\}+\frac{d}{dt}\left\{\sum_{i=1}^{N}\left[\frac{m_i\cdot\left(\dot{x}_{ci/com}^2+\dot{y}_{ci/com}^2\right)}{2}+\frac{I_{ci}\cdot\dot{\phi}_i}{2}\right]\right\}=\left[\sum_{i=1}^{N-1}M_{1,2}\cdot\left(\dot{\phi}_2-\dot{\phi}_1\right)\right]$$

(17)

Although the translational left side of this equation can be divided into terms related to a certain translational direction, the eventual power production, on the right side of this equation, cannot be separated into these directions. Separating the left side of the equation into directional terms, is completely dependent on the chosen global frame; moreover, 'vertical' power can very easily be translated into a 'lateral power' without adding power to the system, e.g. due to centrifugal forces.

5.3 E-gross

This review clearly showed that there arise large differences in mechanical power estimation based on the choice for a model. These differences also impact research studies which estimate metabolic power with gross efficiency calculations (e-gross), which is the ratio between the expended work (metabolic work) and the performed work (mechanical work). E-gross is often determined in a lab, using VO_2-measurements, to convert mechanical work into energy expenditure. Main causes in the differences among athletes and inaccuracies in measurement of e-gross have been ascribed to the metabolic side of the equation. However, determination of the mechanical power with simplified models influences the e-gross estimation evenly well. When only part of the mechanical power balance is determined, for example with a single body model, the dependency of e-gross to the relative movements of the segments is neglected (e.g. de Koning et al. (2005)). If an athlete would then change movement coordination (technique) between the submaximal experiment (where e-gross is set) and the actual experiment, the change in segment motion is neglected in the mechanical power and thus in the metabolic power estimation. Especially for technique dependent sports (e.g. swimming, speed skating), this seems an important fact.

6. Discussion

This review provided an overview of the existing papers on mechanical power in sports, discussing the application and the estimation of mechanical power, the consequences of simplifications, mechanically inconsistent models, and the terminology on mechanical power. Structuring the literature shows that simplifications in models are done on four levels: single vs multibody models, instantaneous power (IN) versus change in energy (EN), the dimensions of a model (1D, 2D, 3D) and neglecting parts of the mechanical power balance. Except for the difference between single versus multibody models in running, no studies were found that quantified the consequences of simplifying the mechanical power balance in sport. Furthermore, inconsistency was found in joint power estimations between studies in the applied inverse dynamics methods, the incorporation of translational joint power, and the integration of joint power to energy. Both the validation on simplification of models and the lack of a general method for joint power or work are research areas well worth investigating.

The terms internal power and external power/work are, apart from the discussion on the actual usefulness of this power separation, confusing, since several meanings were attributed to the terms. The interrelations between the different interpretations of external power have been discussed here. Based on the above, we suggest that it might be more clear to use the terms from the mechanical power balance: joint power (eq. 6), gravitational power (eq. 7), frictional power (eq. 8), environmental power (eq. 9) and kinetic power (eq. 10) and not use the terms internal and external power or work. In case the power due to motion of the COM and due to motion of the segments relative to the COM are to be separated for measurement conveniences, we propose to work with the term Peripheral Power for moving body segments relative to the COM (Zelik & Kuo 2012; Riddick & Kuo 2016). Note however, that these should not be interpreted as separate energy measures (mechanical work). The awareness that terms internal and external work/power are not self-evident and therefore need explanation *and* interrelation to the mechanical power balance, will reduce the possibility of errors and increase the comprehension for the reader. To quote Winter et al. (2016): ' if sport and exercise science is to advance, it must uphold the principles and practices of science.' This review only revealed the tip of the iceberg of the studies concerned with estimating ‘power’ in sport (the search term *power* and *sport* results in 9,751 articles (August 2017)), but illustrates clearly that the sport literature would benefit from structuring and validating the research on (mechanical) power in sports. By structuring the existing literature, we identified some obstacles that may hamper sport research from making headway in mechanical power research.

7. Conclusions

- Performance is not a direct translation of mechanical power.
- Mechanical power is not a direct estimation of muscle power. Mechanical work is also no direct measure of energy expenditure for movement.
- Mechanical power is estimated via the joint power directly, or via the sum of kinetic, frictional, gravitational and environmental power; all other estimations are simplifications.
- Due to limitations in human motion capture in sports, simplified models are employed to determine power. Simplifications in models are done on four levels: single vs multibody models, instantaneous power (IN) versus change in energy (EN), the dimensions of a model (1D, 2D, 3D) and neglecting parts of the mechanical power balance.
- Single body models by definition neglect the relative motion of the separate body segments to the COM of the body. The resulting underestimation in power, as an indication of muscle power, is rarely determined in sports, whereas this part of power is an essential part of the mechanical power balance in technique driven sports as e.g. speed skating, swimming or skiing.
- IN models are more appropriate than EN models for understanding performance of elite athletes. EN automatically results in determination of average power and therefore oscillatory movements are averaged such that positive and negative power would negate each other.
- Little attention is given to the chosen inverse dynamics technique to estimate joint moments and forces, although its influence on joint power estimation is large (e.g. 31% in speed skating).
- When 6DOF joints are applied (e.g. OpenSim, Visual3D), joint forces not only distribute energy, as in the classical 3DOF joint rotational models, but also allow for translational power; Sport researchers should be aware of the differences between these joint power estimations.
- There is no consensus on how negative and positive work in a single joint should be summed. On the same note, there is no standard on whether to allow for energy flow between joints. The chosen approach is not always clear from the articles, although factors of 2.5x difference between approaches have been found.
- The terms external and internal power and work are inconsistent. The terms can easily be replaced by the terms joint power, kinetic power, gravitational power, frictional power and environmental power mentioned in the mechanical power balance of this review paper, which will avoid future confusion.
- Gross-efficiency (e-gross) is not constant within and between athletes. Apart from metabolic causes, this can also be caused by the procedure of mechanical power determination.

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