Title Page

Inverse dynamics, joint reaction forces and loading in the musculoskeletal system: Guidelines for correct mechanical terms and recommendations for accurate reporting of results.

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Abstract

Inverse Dynamics is routinely used in biomechanics for the estimation of loading in the musculoskeletal system but there are problems with the terms and definitions and even official recommendations introduce artificial and incorrect mechanical constructs to justify arbitrary and inappropriate terms. These terminology problems lead to further confusion and misinterpretations rather than to standardisation of mechanically correct nomenclature and accurate interpretation of joint loading. The perspective in this paper exposes some of the flawed foundational premises of these constructs and makes recommendations for accurate reporting of inverse dynamics outcomes and musculoskeletal loading. The inverse dynamics approach is based on free body diagrams that include the actual forces as applied ('Actual Forces' approach) or the replacement of actual forces with an equivalent resultant force and moment ('Resultant Moments' approach). Irrespective of the approach used to model the muscle and other forces, the inverse dynamics outputs always include the joint reaction forces representing the interactions with adjacent segments. The different terms suggested to distinguish the calculated joint reaction forces from the two approaches such as 'net joint force', 'resultant force', 'intersegmental force' and 'bone-on-bone force' are inappropriate, misleading and confusing. It is recommended to refer to joint reaction forces as Total or Partial when using an Actual Forces or a Resultant Moments approach, respectively.

1. Introduction

Despite remarkable progress in biomechanics, some mechanical misconceptions and inappropriate or misleading terms persist, leading to confusion and misinterpretation of mechanical outputs. One of the most controversial nomenclature topics relates to Inverse Dynamics and the estimation of loading in the musculoskeletal system. There has been a long-standing debate and controversy on terminology and interpretation of joint forces calculated through inverse dynamics in relation to musculoskeletal loading. The usual suggestion in the literature including some recent standardisation and official recommendation papers (Derrick et al., 2019; Vigotsky, Zelik, Lake, & Hinrichs, 2019) is to refer to joint forces that are calculated without contributions from internal forces (e.g. muscle and ligament forces) as net joint forces, joint intersegmental forces, or resultant forces. The recommended terms when referring to joint forces that include the contributions of muscles forces in the musculoskeletal model and related free body diagram (FBD) is to use terms such as joint contact forces or bone-on-bone forces (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2014; Vigotsky, et al., 2019; Winter, 2009; Zatsiorsky, 2002). Although these publications clearly highlight an existing controversy and make some useful recommendations, they sometimes also introduce artificial and incorrect mechanical constructs to justify arbitrary and inappropriate terminology recommendations. These terminology problems lead to further confusion and misinterpretations rather than to standardisation of appropriate and mechanically correct terminology. For example, in a recent paper, Vigotsky et al. (2019) make some excellent points about mechanical misconceptions in biomechanics and in particular joint reaction forces, but they also introduce some incorrect interpretations that confuse rather than clarify the inverse dynamics issues. For example, it is stated that 'In biomechanics joint forces come in two flavors' and that one (net joint force) comes from inverse dynamics whereas the other (joint contact force that includes internal force contributions) requires invasive measurements or musculoskeletal modelling. These typical suggestions and recommendations present a concept of different classes or 'flavors' of joint forces. The reality is, however, that there is only a single joint contact force output from inverse dynamics, the joint reaction force (JRF), and this process always involves musculoskeletal modelling irrespective of the complexity of the model and related FBD. The different terms suggested for supposedly different classes or types of forces such as net joint forces, intersegmental forces, resultant forces, bone-on-bone forces etc (e.g.Derrick, et al., 2019; Vigotsky, et al., 2019; Winter, 2009) are, in fact, always referring to the JRF, because this is the only joint force output from an inverse dynamics approach, although the forces contributing to its calculation and its magnitude and direction would vary depending on the complexity and detail of the musculoskeletal model. The aim of this paper is to clarify the inverse dynamics approaches in biomechanics, dispel some myths, confusions and misunderstandings about JRFs and loading in the musculoskeletal system and recommend usage of correct mechanical terms when describing inverse dynamics outcomes.

2. Inverse Dynamics

Biomechanical analysis of human motion usually involves the representation of the human body as a system of interconnected rigid bodies as the mechanics of deformable bodies are too complex. Inverse dynamics is the computational technique that is based on the equations of motion describing the mechanics of a rigid body to calculate the forces and moments acting on the joints and other structures when the kinematics of the rigid body motion and any external forces are known. We typically measure the translational and rotational kinematics with motion analysis systems and measure any external forces, for example the ground reaction forces, using force plates, and then utilise the equations of motion in the inverse direction since the kinematics are known and we calculate the forces and moments required for generating the observed motion. This requires a number of simplifications to be able to represent a biological system and the complex anatomy of a human segment with a mechanical rigid body model. These modelling simplifications result in a FBD for each segment which is the rigid body model and the forces and moments acting on it described in a relevant reference frame linked to the chosen coordinate system (Nigg and Herzog, 2007). The equations of motion for the FBD are usually formulated using the Newton-Euler method (Derrick et al., 2019) and they can be used to explore the dynamics of the modelled mechanical system and calculate musculoskeletal loading through inverse dynamics.

There are two categories of forces included in a FBD: I) Remote Forces and II) Contact Forces (Andrews, 1974; Nigg and Herzog, 2007). It is important to follow the historical development of these methods as the terms used originally were very simple, clear and unambiguous. The FBD is described in detail, for example, by Dempster (1961) and Andrews (1974) and it is specified that the first category of forces (I) are remotely applied forces on the FBD meaning without physical contact; in practice this is the distributed weight force applied usually as a single gravitational force on the centre of gravity of each segment. The second category of forces includes contact forces acting at the proximal and distal joints due to the presence of adjacent segments (IIa) and other contact forces (IIb) acting on the segment anywhere between the proximal and distal joints due to the effects of contact with the external environment or other segments and external structures. These IIb forces include mainly ground contact forces when in contact with the ground, muscle-tendon forces, and other external forces if there is link and contact with another external body such as a dynamometer, sports implement etc. Notice that the only terms used in those original papers are remote and contact forces. Although the original notations for types of FBD forces used by Andrews (1974) such as I, IIa and IIb have not been adopted widely and are instead used for motor unit types in muscle physiology nowadays, they will be used here simply for continuity purposes and to help readers that want to refer to the original FBD papers.

The contact forces at the joints (IIa) are particularly important as they are applied as reactions due to contact with the adjacent segments at the joint(s). The application of the other subcategory of contact forces in a FBD (IIb) is more complex as we require knowledge of the contact conditions with external bodies in order to apply the forces as they act in the correct sense. However, if we do not have the required knowledge to apply the actual forces then an equivalent force and moment can be applied at an arbitrary but appropriate point that will have the same mechanical effect, the equipollent resultant force and moment (Andrews, 1974). These two approaches lead to two distinct inverse dynamics formulations and one of the best and very clear descriptions of these two approaches is given by Nigg and Herzog (2007) who use the terms 'Actual Forces and Moment' approach' and 'Resultant Forces and Moments approach' (simplified as 'Actual Forces' or 'Resultant Moments' here). In practice, the different type IIb contact forces can be described using either approach depending on the knowledge we have for their application. For this reason, we normally end up with a mixed approach where the FBD usually includes some category IIb contact forces such as ground reaction forces (GRFs) applied as they act (Actual Force) and other IIb contact forces, such as muscle forces, replaced with equivalent resultant moments (Resultant Moment). This is normally because we do not have detailed anatomical information about the geometry of their application onto the musculoskeletal system although such information exists for many situations (e.g. Tsaopoulos, Baltzopoulos, Richards, & Maganaris, 2007). We also have to reduce a number of muscle forces to a single moment to avoid an indeterminate system with a single moment equation and many unknown muscle forces. The important point here is that these formulations (Actual Forces, Resultant Moments, or a mixed approach) are all mechanically equivalent with the same system dynamics since any equipollent resultant forces and moments have exactly the same mechanical effect with the actual force distributions they replace.

It will be easier to follow the arguments presented by considering a detailed example of a single segment, two-dimensional inverse dynamics application along the lines of the model in Vigotsky, et al. (2019). An isometric knee extension is assumed with a seated person holding the lower leg in a horizontal position with the knee fully extended by activating the knee extensors to overcome the weight of the segment. This is a static action with no movement in the knee joint and both rotational and translational accelerations are zero. The two segmental axes in this position are assumed to coincide with the global horizontal (X) axis (segment long axis-compressive) and vertical (Y) axis (shear segment axis). There is contact at the proximal joint only (knee) with the upper leg segment. The other end of the segment is free and there is no distal joint since the FBD model describes the lower leg-foot as the terminal segment in the kinetic chain of the lower limb. For this reason, forces due to contact with the adjacent segment are only applied at the knee (see Figure 1). We have to follow the Resultant Moments approach if we do not have information about the actual application of the muscle force or to reduce the number of unknown muscle forces to a single unknown parameter, the equivalent joint moment they generate, and avoid an indeterminate system. In this approach we simply apply the equivalent knee extension moment M_m and a total JRF resolved into components R_X and R_Y along the two axes as depicted in the FBD for this approach in Fig. 1 (Left Panel). In the Actual Forces approach, the actual muscle force vector (F_m) is applied to the FBD instead of an equipollent moment and force. This can be achieved by modelling the action of the patellar tendon based on findings from the literature. In one of our previous studies, for example, we examined the orientation of the patellar tendon relative to the tibia over a range of knee angles and its moment arm (d_m) *in vivo* during maximum voluntary contractions (Tsaopoulos, et al., 2007). Based on this information the resulting FBD with the Actual Forces approach is shown in the right panel of Fig. 1.

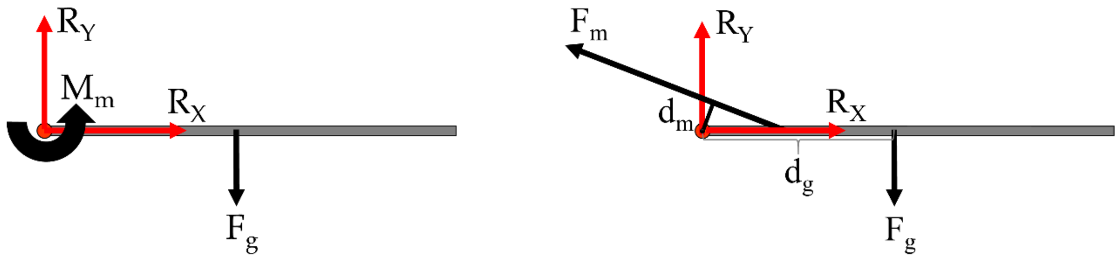


Fig. 1. Free body diagram for the isometric knee extension example using the 'Resultant Moments' approach (Left panel) and the 'Actual Forces' approach (Right panel) that also shows the moment arms of the gravitational force (d_g) and the muscle force (d_m).

In this simplified 2D approach and irrespective of the inverse dynamics approach followed, the general forms of the three equations of motion (Newton-Euler formulations of equations for rotation and translations along the two axes) are exactly the same and can be written as:

$$\sum_{i=1}^{Mmax} M_i = I\alpha$$

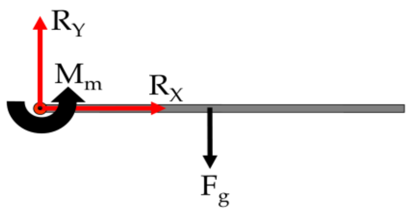
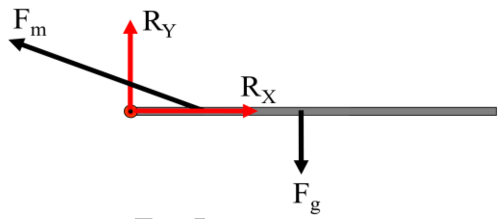
$$\sum_{i=1}^{Xmax} Fx_i = ma_x$$

$$\sum_{i=1}^{Ymax} Fy_i = ma_y$$

where:

M_i the moments (i=1…Mmax) acting on the FBD system, Fx_i the components (i=1…Xmax) of all the actual forces acting along the compressive axis and Fy_i the components (i=1…Ymax) of any actual forces acting on or parallel to the shear axis of the FBD. The equations of motion are treated independently and sequentially so we use the same index i that takes different values in each equation. I is the moment of inertia of the segment and m the mass but since the angular (α) and linear accelerations (a_x and a_y) are zero in this isometric joint action example, the second parts of the above equations are all zero. Table 1 includes the FBDs and the general equations of motion, the expanded equations of motion for rotation and translation along the two axes and the given and calculated parameters when the two different inverse dynamics approaches are implemented.

Table 1. Free body diagrams, general and expanded equations of motion, and given (input) and calculated (output) parameters when the inverse dynamics formulation is based on a FBD model using a 'Resultant Moments' or an 'Actual Forces' approach for the knee extension example. In the 'Actual Forces' approach the muscle force vector (F_m) can be replaced by its two components along the horizontal (F_{mx}) and vertical axis (F_{my}). Both approaches will usually have the same number of moments included in the inverse dynamics formulation so index n is common but typically p<k and q<m

	Inverse Dynamics Approach (2D Single Segment)	
	'Resultant Moments'	**'Actual Forces'**
Free Body Diagram		
General Equations of Motion	$\sum_{i=1}^{n} M_i = I\alpha$ $\sum_{i=1}^{p} Fx_i = ma_x$ $\sum_{i=1}^{q} Fy_i = ma_y$	$\sum_{i=1}^{n} M_i = I\alpha$ $\sum_{i=1}^{k} Fx_i = ma_x$ $\sum_{i=1}^{m} Fy_i = ma_y$
Rotation	$M_m - F_g \cdot d_g = 0$	$F_m \cdot d_m - F_g \cdot d_g = 0$
Translation X Axis (Compressive)	$R_x = 0$	$R_x - F_{mx} = 0$
Translation Y Axis (Shear)	$R_Y - F_g = 0$	$R_Y + F_{my} - F_g = 0$
Input:	$F_g = 39.2$ N $d_g = 0.19$ m	$F_g = 39.2$ N $d_g = 0.19$ m $d_m = 0.03061$ m
Output:	$M_m = 7.45$ Nm $R_x = 0$ N $R_Y = 39.2$ N	$F_m = 243.5$ N $R_x = 225$ N $R_Y = -54$ N

Notice that the JRF is represented in the FBD by its two components in the two different axes (R_X and R_Y) and although these are drawn generically using the same vectors acting along the positive directions in both axes, the actual JRF components calculated from a Resultant Moments approach are typically significantly lower and may act in different directions compared to the JRFs from the Actual Forces approach. Both inverse dynamics approaches will be followed in this example to calculate the loads in the musculoskeletal system, demonstrate the problems with incorrect terminology and the resulting misunderstandings and confusion.

2.1. Resultant Moments Approach

The moments equilibrium equation for rotation in the formulation for this approach (see Table 1, left panel) is:

M_m-$F_g \cdot d_g$=I$\Rightarrow\alpha\cdot M_m$-$F_g \cdot d_g$=0, since α=0 and the moment arms of R_X and R_Y are zero since, by definition, they are applied on the origin of the system intersected by the axis of rotation. The muscle moment M_m is the only unknown in this equation when substituting the gravitational force (F_g=39.2 N) and its moment arm (d_g=0.19 m) so:

M_m-39.2·0.19=0$\Rightarrow M_m$=7.45 Nm

In this formulation, the only force acting along the X axis is the compressive component of the JRF (R_x) since it was not possible to model the actual muscle force and resolve it to its components along the two axes:

$R_x = m\cdot a_x \Rightarrow R_x$=0 N

This inverse dynamics approach output includes the JRFs but the R_x in this case is 0 N given that this is the only force that we modelled in the X direction of the FBD and we have a static condition (a_x=0). Solving the equation of motion for translation along the Y axis gives R_Y=39.2 N.

2.2. Actual Forces Approach

The moments equilibrium equation formulation for this approach under static conditions (see Table 1, right panel) is:

$F_m \cdot d_m$-$F_g \cdot d_g$=0

When substituting the muscle moment arm value (d_m=0.03061 m), the gravitational force (F_g=39.2 N) and its moment arm (d_g=0.19 m) to this equation, the muscle force is the only unknown so we can solve for F_m:

F_m·0.03061-39.2·0.19=0$\Rightarrow F_m$=243.5 N

Having solved for F_m, notice that the muscle moment $M_m=F_m \cdot d_m=7.45$ Nm is the same with both approaches as expected from the equations of motion for rotation in Table 1. The equations of motions for translation are applied separately in the two axes using this analytical vector approach so the calculated F_m must be resolved and replaced by its two components F_{mx} and F_{my}. It is possible to resolve F_m to its two orthogonal components and determine F_{mx} and F_{my} since the magnitude of F_m was calculated from the moments equilibrium equation and its orientation relative to the compressive axis is known (Tsaopoulos, et al., 2007). This is shown in Fig. 2 where $F_{mx}=F_m\cdot$

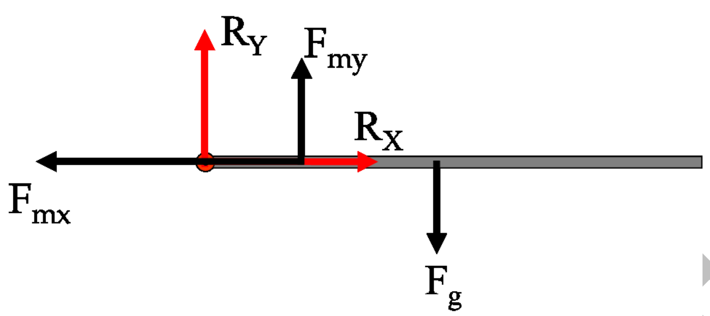


Fig. 2. Free body diagram for the isometric knee extension example using the 'Actual Forces' approach but with the muscle force vector replaced by the two equivalent components along the horizontal (F_{mx}) and vertical axis (F_{my}).

We can then use the equations of motion for translation to calculate the JRF components in each axis and we obtain $R_X=225$ N and $R_Y=-54$ N as shown in Table 1 (Output row for 'Actual Forces'). Notice that the calculated JRF in the shear direction is negative which signifies that it is actually acting in the opposite direction to the positive R_Y force vector drawn in the FBD.

The shear component of the JRF calculated in this approach (-54 N) is higher and in the opposite direction to the JRF shear force calculated through the Resultant Moments approach (39.2 N). Table 1 contains a summary of the two different inverse dynamics modelling approaches and the resulting outputs.

It is important to highlight that both approaches are mechanically equivalent and the behaviour of the mechanical system would be exactly the same, that is to say, if one applied the forces and moments as described in either approach, there will be no translation in either axis and no rotation as expected in this static condition. The FBD will be describing the segment in that extended static position as the subject is activating the knee extensors to overcome the weight of the segment and keep the knee extended with the lower leg in a static horizontal position.

It is also important to consider that the inverse dynamics output, irrespective of the approach followed (‘Actual Forces’ or ‘Resultant Moments’), always includes the joint reaction forces R_x and R_Y. It is obvious from the above example that the JRF components R_X and R_Y calculated from a Resultant Moments approach are significantly lower and may act in different directions compared to the JRFs from the Actual Forces approach. For example, the JRFs from the Resultant Moments approach, in the context of the lower leg segment and motion modelled, would indicate that there is no compressive load (R_x=0) absorbed by the meniscus and tibia. The shear JRF (R_y=39.2 N) would indicate that the Posterior Cruciate Ligament (PCL) is actually loaded and provides the majority of the shear force applied on the tibia. However, when the actual extensor muscle force and the way it is applied is modelled (assuming this knowledge exists from literature or own measurements), then the JRFs indicate that there is a compressive load (R_x=225 N), the shear load is higher and actually applied in the posterior direction (R_y=-54 N). This is a force that will be provided mainly by the Anterior Cruciate Ligament (ACL), indicating an ACL rather than a PCL load.

3. Discussion and Implications

The description of the inverse dynamics approaches and the worked example illustrated the problems with terms and resulting misinterpretations of joint loading. The usual terminology recommendations and suggested convention in the literature and recent standardisation papers is to use terms such as ‘net joint forces’, ‘resultant joint forces’ or ‘intersegmental joint forces’ to refer to JRFs that are calculated through a Resultant Moments approach and do not include the contributions of muscle forces. It is also proposed that these forces should not be confused with ‘bone-on-bone’ or ‘joint contact’ forces (Derrick, et al., 2019; Vigotsky, et al., 2019; Zajac, Neptune, & Kautz, 2002) that describe the loads experienced across the joint surface and include muscle force contributions. Although it might be a very good suggestion to have a way to differentiate JRFs when calculated through an Actual Forces or a Resultant Moments approach, the fact is that they are always the calculated JRFs (category IIa contact forces in the general description of forces acting in a FBD), irrespective of the inverse dynamics approach used to calculate them.

Why are the terms 'net joint forces', 'resultant joint forces' or 'intersegmental joint forces' inappropriate for differentiating JRFs?

A net or a resultant force is the vector sum of a number of forces. The JRF components R_X and R_Y are equal and opposite to the sum of all the forces acting on or parallel to the X and Y axes so, by definition, they are net or resultant forces irrespective of the inversed dynamics approach used. For example, the R_Y whether calculated through the Actual Forces (R_Y=-54 N) or Resultant Moments (R_Y=39.2 N) approach is equal and opposite to the net or resultant of all the other shear (Y axis) forces. All JRFs are also, by definition, intersegmental (acting between or across segments) because they are caused as a reaction to the forces (action) applied by the segment analysed to the adjacent segment, but this is irrespective of the inverse dynamics approach followed. For example, the contact forces R_X and R_Y are reactions (equal and opposite) to the forces applied by the lower leg to the adjacent segment (upper leg) so they are equilibrant forces in structural mechanics terminology. The detailed FBD for the above Actual Forces approach example is shown again in Fig. 3 but with the reaction force vectors R_X and R_Y drawn to scale and pointing in the actual direction they are acting since their magnitude and direction (sign) were calculated above. The joint reaction force R is thus resolved to its components R_X and R_Y along the two orthogonal reference frame axes X and Y that align with the long axis of the segment (compressive axis) and the shear axis, respectively, with the origin of the reference frame at the joint centre.

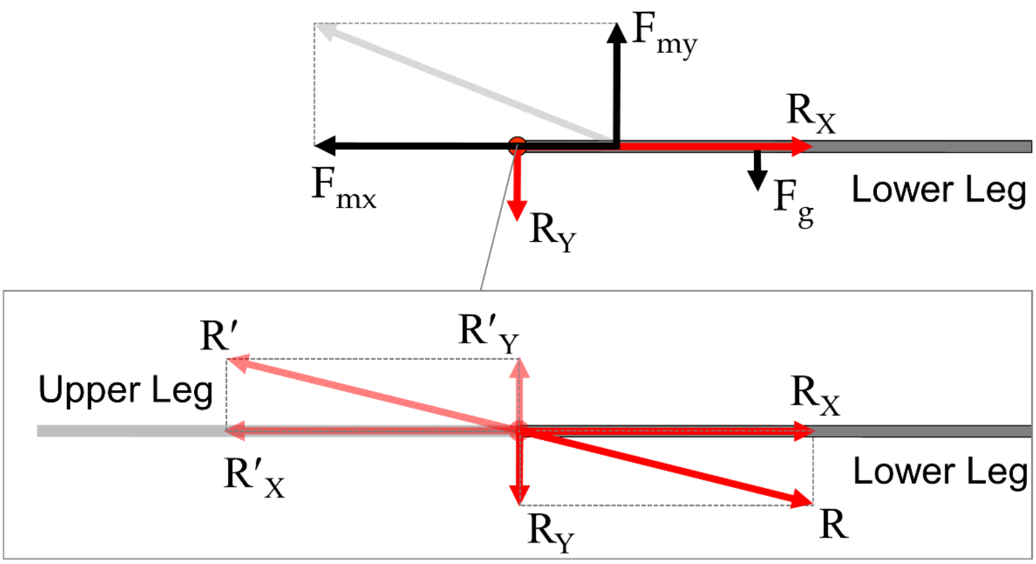


Fig. 3. Free Body Diagram of the lower leg (at the top of the figure) showing the forces acting during the static knee extension example. The forces are shown as applied and resolved into components along the two axes and are drawn approximately to scale following the inverse dynamics calculations. The insert at the bottom of the figure shows the reaction forces acting at the joint between the free body diagrams of the lower and upper leg.

The insert in the bottom of Fig. 3 shows the detailed depiction of the reaction forces for the FBDs of both the lower and upper leg connected at the common joint. In the strict mechanical sense, the net or resultant of all category I and IIb forces acting on the lower leg is R' and this is applied on the upper leg segment due to contact at the joint. The equal and opposite reaction at the joint or equilibrant force R that is applied by the upper leg to the lower leg as a reaction to R' is what we include in the FBD of the lower leg since the system of interest for our mechanical analysis is the lower leg. The net force R' applied to the upper leg by the lower leg and the mechanics and motion of the adjacent segment are of no relevance for our inverse dynamics analysis of the lower leg segment. We are only concerned with the equal and opposite (equilibrant) joint reaction forces R_X and R_Y (category IIa forces) that are applied as a reaction by the adjacent segment on the FBD of the segment we are currently examining. This is similar to when there is contact with the ground in which case we are interested in the ground reaction force (GRF) as the equal and opposite reaction to the net force applied by the terminal segment to the ground.

The terms 'net joint forces', 'resultant joint forces' or 'intersegmental joint forces' are therefore inappropriate for describing JRFs calculated only through the Resultant Moments approach because the JRFs calculated through an Actual Forces approach are also net or resultant and intersegmental forces.

Why are the terms 'bone-on-bone forces' and 'joint contact forces' inappropriate for differentiating JRFs?

These terms are also inappropriate for differentiating JRFs because they express load on different structures and not only bones and irrespective of the inverse dynamics approach followed. The calculated JRFs represent forces exerted by or on different structures such as ligaments, cartilage etc and not only bones. Furthermore, although a component of the JRFs will be exerted on bones, this is not only the case when the Actual Forces approach is followed. For example, the shear component of the JRF (R_Y) will be expressing a shear load on the tibia bone but this will be the case irrespective of whether it was calculated through the Actual Forces (R_Y=-54 N) or Resultant Moments (R_Y=39.2 N) approach. So it is inappropriate to restrict the term 'bone-on-bone force' only to JRFs calculated through the Actual Forces approach as JRFs describe loads on bones (as well as other tissues) when using both the Resultant Moments and the Actual Forces approaches. There is a typical argument used in several books (Robertson, et al., 2014; Winter, 2009; Zatsiorsky, 2002) to justify the differentiation of the two supposedly different forces ('joint reaction' and 'bone-on-bone') by highlighting that if there is co-contraction of muscles in a static joint, for example by simultaneous activation of the main agonist and antagonist muscles, then the load that will be experienced by bones will be different compared to the joint load with no muscle activation, whereas the JRF will be the same in both cases. This is a fallacious argument, however, because if it is known that there is co-contraction that is not modelled in the FBD then of course the JRF will be miscalculated (underestimated) since there were forces acting that were not included in the inverse dynamics approach. The calculated JRF is always specific to the complexity of the system and constrained by the simplifications and assumptions of the musculoskeletal model used in the inverse dynamics approach. If the muscle co-contraction forces acting were included in the model then the correct JRF will be calculated and will be equal to the so called 'bone-on-bone' force. In both cases, however, with or without co-contraction, if the muscles forces acting were included in the FBD and the inverse dynamics calculations, then the JRFs will be calculated correctly and will be reflecting the loads experienced by the bones and other tissues absorbing loads in the joint. Not including known acting forces in the FBD is not a rational argument but a flawed foundational premise to support the existence of a supposedly different category of force ('bone-on-bone force') when, in fact, what is being described as a joint reaction force different from the 'bone-on bone' force is, in fact, an incorrectly calculated JRF. This of course will be lower than the true JRF since there was no attempt to model and include known muscle forces acting on the segment. What is termed 'bone-on-bone' force isn't a separate category or type of force outside the standard inverse dynamics formulation that is different to the JRF. It is in fact the correct JRF that would be calculated if all the known forces acting were included in the FBD. This might be technically challenging and the restriction of only one unknown force in the formulation would still apply but it is possible, for example, to predict or estimate one of the two forces, the antagonist muscle force, from EMG (e.g. Kellis and Baltzopoulos, 1997; Kellis and Baltzopoulos, 1999). If this was applied in the above example, then the complexity of the musculoskeletal model will be increased by including the EMG-estimated antagonist muscle force in the FBD model and the calculated JRF will be different reducing the shear load and increasing the compressive load. Will these JRFs be a different, third 'flavor' then? The answer, of course, is no because they are the same JRF components R_X and R_Y but they will have different magnitude and direction as we used a more detailed musculoskeletal model. There are no different 'flavors' of joint forces but a single JRF output from inverse dynamics (the category IIa contact force R) although its magnitude and direction (reflected in the calculated components R_X and R_Y) would depend on the complexity of the model as determined by the number of other contact forces (IIb) between the proximal and distal joints included in the FBD and the way they are modelled (Actual Force vs Resultant Moment).

It is also inappropriate to restrict the term 'joint contact force' only to JRFs calculated through the Actual Forces approach when they include muscle force contributions because JRFs are joint contact forces (category IIa FBD contact forces) irrespective of the inverse dynamics approach. These JRFs express some of the joint contact force and joint load even when calculated without the contribution of muscle forces in a Resultant Moments approach. There is also a misconception that inverse dynamics relates only to the calculation of joint moments and JRFs that do not include contributions of internal forces (from muscles, ligaments etc), whereas the calculation of joint contact forces that include contributions of muscle and other internal forces requires musculoskeletal modelling or invasive measurement (Vigotsky, et al., 2019), implying somehow that these techniques are different from inverse dynamics. This is a serious misunderstanding because musculoskeletal modelling is involved in every inverse dynamics approach (Nigg, 2007) as it is required in the process of constructing any FBD by making simplifications and representing the segmental components and mechanics that result in a more simplified (Resultant Moments approach) or more complex (Actual Forces approach) inverse dynamics formulation. There is also a pejorative bias in several papers that address mechanical terminology issues by targeting and criticising only sport biomechanics or sport sciences (e.g. Vigotsky, et al., 2019; Winter et al., 2016) when these terminology and misinterpretation issues originate from and/or are present in many other areas and applications including biomedical, clinical, rehabilitation or human movement biomechanics in general.

What is the appropriate terminology for JRFs in inverse dynamics?

The above analysis should have clarified that the output of any inverse dynamics approach includes the unknown muscle force or moment and the relevant joint contact (reaction) forces. The magnitude and direction of these JRFs will obviously be different depending on the complexity of the model and whether an Actual Forces or a Resultant Moments approach was followed. However, in both cases the JRFs are net or resultant, intersegmental, contact forces and act on or load both bones and other structures. For these reasons, the suggestion to restrict these terms to JRFs from one or the other inverse dynamics approach only is arbitrary, contentious and inappropriate. An appropriate means to differentiate the JRFs calculated from the two inverse dynamics approaches will be to use a term such as Total JRF when referring to the JRF from the Actual Forces approach as this will include contributions from all the forces acting (within the simplifications and assumptions of the FBD model) and Partial JRF when using a Resultant Moments approach. The inverse dynamics approach followed should also be specified (Actual Forces or Resultant Moments) when discussing musculoskeletal loading rather than rely on artificial, arbitrary and sometimes incorrect or inappropriate terms. The suggested term 'Total' refers to the maximum JRF calculated with the specific FBD used when all the included forces (following the necessary musculoskeletal modelling simplifications) are applied on the FBD as they act. If any of the forces assumed to be acting on the segment are replaced by equipollent moments and forces in a Resultant Moments approach, then the calculated JRF will always be less than the total JRF calculated when all the forces applied on the FBD are modelled as they act using an Actual Forces approach. Therefore, the partial JRF calculated from a Resultant Moments approach must not be used for estimating joint loading in inverse dynamics applications. The total JRFs from an Actual Forces approach must be calculated when investigating joint loading but it must be stressed that even the JRFs from an Actual Forces approach are only estimated approximations of the actual loads experienced in the real joint. This is simply a consequence of the inevitable simplifications, reductions and approximations of all inverse dynamics approaches that are necessary to represent the real and complex musculoskeletal system with a simplified mechanical model.

In most biomechanics applications involving multi-segment inverse dynamics analyses, separate FBDs are required for each segment and we normally start with the most distal or terminal segment (usually the foot). In these multi-segment approaches, the calculated moments and forces at the proximal joint (ankle) of the most distal segment (foot) have to be applied as reaction moments and forces at the distal joint of the next segment (lower leg) for the inverse dynamics analysis of that segment to be calculated. This process is repeated with the next segment up the kinetic chain (upper leg, pelvis etc). In such multi-segment inverse dynamics analyses (Winter, 2009; Zatsiorsky, 2002), it is very convenient to use the Resultant Moments approach because it eliminates the need to model the application of muscle and other forces accurately at each intermediate joint, there is only one unknown parameter in the moments equilibrium equation avoiding indeterminate systems and it is easier and more effective computationally. This is the main reason that it is usually the inverse dynamics approach implemented in motion analysis and musculoskeletal modelling software. The misinterpretation problems usually start when the calculated partial JRFs from a Resultant Moments approach are used to estimate joint loading with this inverse dynamics formulation. This discrepancy in the interpretation of joint loads, however, is not caused because the calculated forces are not JRFs or they are not correct and it certainly cannot be solved by arbitrary and inappropriate labels that are suggesting different categories or types of forces but, in fact, they always refer to the JRFs. If one needs to know exact directions of the total joint force in a particular direction (compressive or shear for example), then they need to make the effort and obtain the information that will allow modelling of all the contributing forces as they act in both the proximal and distal joints using an Actual Forces inverse dynamics approach for the last segment and joint of interest. This is something that was known ever since the early applications in biomechanics with Paul (1966) stating 'To obtain the true value of the joint force components at any instant would require a knowledge of the directions of pull of the muscles at that instant and the magnitude of the force exerted by each'. The only possibility to use the Resultant Moments approach for joint loading assessment would be to distribute the calculated joint moments at both the proximal and distal joints to the contributing forces using optimisation techniques (e.g. Tsirakos, Baltzopoulos, & Bartlett, 1997), and then re-calculate the total JRF. However, optimisation techniques also require knowledge or estimation of various muscle parameters or variables such as moment arm/line of action, physiological cross-sectional area or maximum force etc.

4. Conclusions

In human motion biomechanics the inverse dynamics approach is based on FBDs that include the actual forces as applied or the replacement of actual forces with an equipollent resultant force and moment. Irrespective of the approach used to model the muscle forces ('Actual Forces' or 'Resultant Moments'), the inverse dynamics outputs are always the JRFs calculated from the equations of motion for translation and representing the interactions (reaction contact forces at the joints) with adjacent segments. The 'Resultant Moments' approach is very convenient as it avoids indeterminate systems and is implemented in multi-segment inverse dynamics analyses but the JRFs calculated are only the partial joint contact forces since they do not contain the contributions from muscle forces that were replaced by an equivalent moment. The total joint contact forces can only be calculated with the 'Actual Forces' approach and if these forces are the focus of the investigation for determining joint loading, then the 'Resultant Moments' approach should not be used for that segment. The different terms suggested and recommended to distinguish the calculated JRFs from the two different approaches are inappropriate, misleading and confusing because the JRFs from either approach are always, net or resultant forces, intersegmental, and represent some or all of the load on bones and other joint tissues.

Guidelines for accurate reporting of inverse dynamics outcomes and musculoskeletal loading using mechanically correct and appropriate terms:

- Always report the approach used to model muscle force(s): 'Actual Forces' or 'Resultant Moments'
- Refer to JRFs as Total or Partial depending on whether an 'Actual Forces' or 'Resultant Moments' approach was, respectively, used
- If accurate joint loading estimation is required then an 'Actual Forces' approach should be used for the calculation of the total JRF, at least for the segment(s) and joint(s) of interest, by an attempt to use a more detailed musculoskeletal model with the actual application of the main muscle force in the FBDs of those segments
- If a 'Resultant Moments' approach is the only option for the inverse dynamics analysis, then this should be reported and only the calculated joint moment should be used. The partial JRF calculated with this inverse dynamics approach should not be used for joint loading estimation.
- The terms 'net joint force', 'resultant force', 'intersegmental force' and 'bone-on-bone force' should not be used to distinguish JRFs from different inverse dynamics approaches. All JRFs are net or resultant, intersegmental and express some bone loading, irrespective of the inverse dynamics approach used for their calculation.

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