TOWARDS A "MORE VALID" METHOD OF VALIDATION: APPLICATION OF EFFECTIVE MASS FOR ERROR RESOLUTION OF FORCE PLATE MEASUREMENTS

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We introduce effective mass as the preferred alternative to total system mass when analyzing a multi-link model of the human body. Effective mass is defined as the mass that would have equivalent motion characteristics at the point of force application if substituted for the whole system. We demonstrate our findings by deriving formulations for loaded back squat and bench press exercises. Our results suggest that force-plate-derived metrics such as velocity and power contain non-trivial errors when total system mass is used to infer kinematics of external loads. We elaborate on the sources of these errors and how they can compromise the assessment of the validity or reliability of other devices, such as linear position transducers and IMU-based tools.

KEYWORDS: effective mass, force plate, validation.

INTRODUCTION: In the context of the human body as a multi-link dynamical system, it is unrealistic to assume that the full-body kinematics resemble that of the external load (point-mass equivalency) during strength training exercises. Yet, this assumption is commonly observed in the sports science literature, especially when a force plate (FP) is used to assess physical performance (Askow et al., 2018; Zink, Perry, Robertson, Roach & Signorile, 2006). This assumption introduces errors that are often unnoticed in practice but which could impact movement assessment and interpretation of performance metrics.

Effective mass (EM) of a mechanical system is a physical property adopted in the analysis of multi-body systems (or systems with multi-physics sources of force, e.g., electrons where gravity, electrical, and electromagnetic forces influence the movement) to simplify the internal kinematics by replacing them with the kinematics of a point mass (Christie, 1952). The new system represents the original kinematics while preserving its total kinetic energy. It moves at the same velocity as a point of interest in the original system and its mass depends on the configuration of the original system at any given time. Therefore, to find the accurate mass of the new system (EM), original system's internal kinematics need to be studied. The variations of EM are studied in systems such as the mass-spring system (Leclerc, 1987), study of human gait (Chi & Schmitt, 2005), and solid-state physics (Silveirinha & Engheta, 2012). The errors caused by using total system mass instead of the effective mass in the above applications are often too large to be ignored. EM can range from values that are more than the total system mass (Sánchez & Pugnaloni, 2011) to negative values in systems with oscillating movements (Khamehchi et al., 2017; Yao, Zhou & Hu, 2008). However, in strength training exercises, the errors may not seem as obvious, especially since the metrics can remain consistent despite the errors. Banyard, Nosaka, Sato, & Haff, (2017) compared the outputs of two commercially-available devices to measure velocity and power of strength-training exercises to the output extracted from FP. It is evident (though not noted in the paper) from the reported results that mean and peak power metrics that the LPT device reports are considerably larger than the expected values from FP. The errors seem to reduce as the load approaches athletes' 1RM. Accordingly, the purpose of this project is to introduce the application of EM to evaluate the impact of the point-mass equivalency assumption on the accuracy of the metrics calculated from FP to represent the kinematics of the external load in common strength training exercises.

METHODS: We performed a theoretical study analyzing kinematics of loaded back squat (BS) and bench press (BP) exercises and derived formulae that show how EM is affected by anatomy, musculoskeletal synergy (how limbs move with respect to each other during a movement), and load relative to total system mass. We then simulated variations of EM during the concentric phase of the exercises using a custom script (R version 3.3.2) that implements the derived formulae, takes in movements of the limbs as input, and provides EM values with respect to body mass as output. A commercially-available IMU-based device (PUSH band 1.0, 200Hz, PUSH Design Solutions Inc.) was used to collect sample angular velocities for limbs from a single participant (male, age = 29 y, height = 1.70 m, body mass = 62 kg) to use in the simulations. The gyroscope of the device had a full-scale range of ±2000 dps with a sensitivity of 0.061 dps, a total RMS noise of 0.1 dps, and a typical nonlinearity of ±0.1%. (InvenSense Inc., 2013). IMU was attached by a strap to the participant's upper arm (for BP) or thigh (for BS).

Two system parameter variations were simulated to study their effects on EM. The parameters were load relative to total system mass (for BP) and femoral length relative to total body height (for BS).

The effective mass was derived by equating the total kinetic energy of the system to the kinetic energy of a hypothetical mass that is moving at the velocity of the point of interest (here barbell velocity), i.e.

$$K_{total} = \frac{1}{2} m_{effective} v^2 \quad (1)$$

where K_{total} is the total kinetic energy of the system comprising translational and rotational kinetic energies of all components of the system, $m_{effective}$ is the EM of the system, and v is the velocity of the point of interest. So, $m_{effective}$ will be a function of all the mass elements that contribute to K_{total}, the limbs' length that indicate how the velocities of each limb relate to v, as well as the configuration of the system at any time (i.e., limb angles).

RESULTS: Equations (2) and (3) show the EM as functions of system properties for BP and BS, respectively.

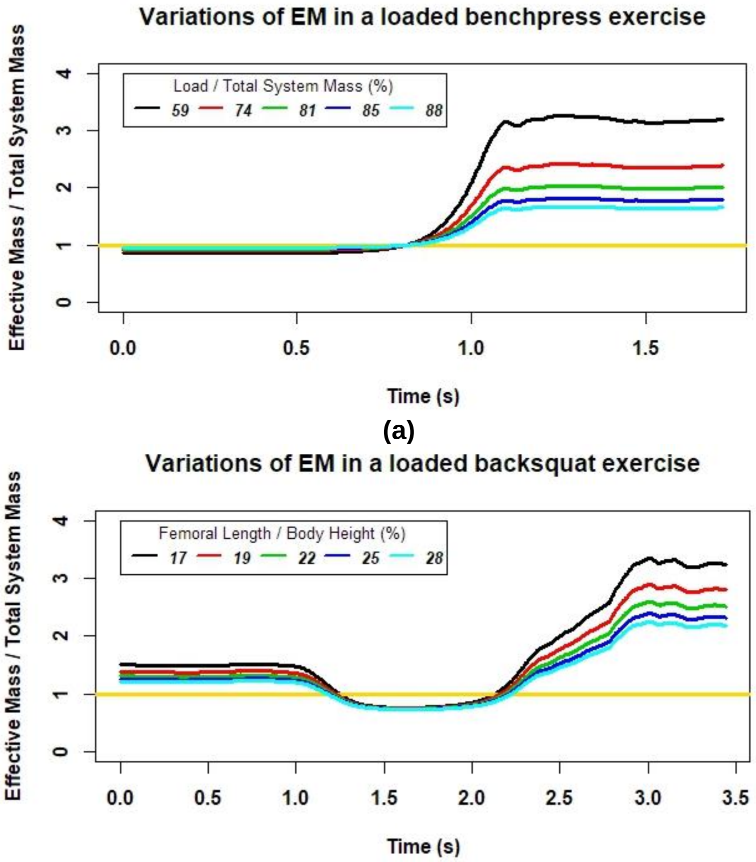
$$m_{effective}{}^{BP} = \frac{(r_g{}^2 + r_1{}^2)}{(l_1 cos(\theta))^2} \times m_1 + m_2 + m_3 \quad (2)$$

$$m_{effective}{}^{BS} = A^2[I_2 + m_2 r_2{}^2 + I_3 B^2 + m_3(l_2{}^2 + r_3{}^2 B^2 - 2 l_2 r_3 B cos(\alpha + \beta))] + m_4 \quad (3)$$

where m_i's, l_i's, r_i's, and I_i's are the mass, length, distance of COM of the limb to the corresponding joint, and the mass moment of inertia of the upper arm, forearm and external load (for BP), and shanks, thighs, torso, and external load (for BS). r_g is the radius of gyration of the upper arm, and θ, α, β are angles of upper arm, femur, and torso with respect to the horizontal line, respectively, and

$$A = \frac{1}{l_2 cos(\alpha)(1 + tan(\alpha) cot(\beta))}$$
$$B = -\frac{l_2}{l_3} \frac{sin(\alpha)}{sin(\beta)} \quad (4)$$

The variations of EM in loaded BS and BP for different loads and femoral lengths, respectively, are shown in Figure 1. The horizontal line in each graph indicates the equivalency threshold (where EM equals total system mass). As can be seen, EM varies substantially during the concentric phases of both exercises. In BP, where total system mass is the external load plus the mass of the arms, concentric phase starts with EM values that are less than the total system mass (upper arm angle = -10 degrees). As the barbell is lifted, EM increases and reaches the total system mass at a specific point where COM moves at the same velocity as the external load. It then increases and ends with values that are two to three times larger than the total system mass. Figure 1.a shows that this final value increases as the ratio of the load over total system mass decreases. Therefore, we can expect that at heavier loads, the errors of point-mass assumption is smaller which confirms the results observed in Banyard, Nosaka, Sato, & Haff, (2017).



(a)

(b)

Figure 1: Variations of EM during concentric phase of BP (a) and BS (b) exercises using simulated anthropometric parameters.

For BS, since there are more limbs involved in the movement (whose rotational kinetic energy is ignored in the point-mass equivalency assumption), EM shows more complex variations. In Figure 1.b, the concentric phase starts at $t = 1s$ and finishes at $t = 3s$. This figure also shows that the final EM value depends on the anatomy of the athlete (here, ratio of femur over athlete's height). Shorter ratios tend to result in higher EM values throughout the execution of the rep.

DISCUSSION: Since EM is an indicator of how the velocity of COM differs from the velocity of the point of interest (e.g., barbell velocity), the acceleration (and thus velocity and power) values that are computed from FP signals may not necessarily describe the movement of the external load, even though they accurately represent the kinematics of COM. There are more mass components involved in the total kinetic energy of the system in BS. This, in turn, means that a potentially-larger portion of the total kinetic energy due to the rotational movements of the body limbs in BS is ignored in the point-mass equivalency assumption. Thus, it can be inferred that one main cause of the differences between EM variations in the two exercises is the internal dynamics of the system during the execution of the exercises.

In the analysis of the kinematics of movement using FP, the vertical ground reaction force (GRF) is used as the force to calculate the acceleration of COM. It is of crucial importance to note that this acceleration is not equivalent to the acceleration of the external load since the barbell traces through a different trajectory in space than COM. The power that is calculated from FP, however, is the true representation of the total system power in the vertical direction if the velocity profile is generated from FP outputs (using total system mass) and vertical GRF is used as the effective force in power calculations. Nevertheless, this power value is not equivalent to the outputs of commercially-available linear position transducers (LPTs) since they may not measure the kinematics of COM while attached to the barbell. So, FP may not

be the right tool to validate the outputs of such devices unless the EM of the system is incorporated instead of the total system mass.
Motion capture systems can be used either as an alternative to or alongside with FP to calculate velocity and power metrics. Since the movement of most body limbs can be measured, the kinematics of COM can be estimated through multi-body modelling; and the kinematics of the external load can also be recorded. The former analysis is equivalent to calculating COM kinematics from FP and the latter provides comparable outputs to LPTs; but the two analyses would not necessarily be comparable since they measure the kinematics of different points in space.

CONCLUSION: Incorporating the total system mass for calculating velocity of any point of interest other than COM can result in erroneous outputs in common strength training exercises. Such errors can further inflate as velocity and force are fused to calculate system power. One implication of this is that the discrepancies in features (e.g., power) that are found between devices (e.g., FP vs LPTs) may reflect the fact that these devices measure the features at different points in space (FP measures COM whereas LPTs measure barbell velocity) and are not necessarily due to the errors involving the validity of the tool in question. Thus, researchers should take caution while extracting performance metrics for evaluating the outputs of different tracking devices compared with FP.

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