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Health & Movement Sciences

Improved estimation of the whole-body center of mass, a step ahead in biomechanical analyses of balance control.

Jaap van Dieen *based on peer reviews by* ***Guillaume Durandeau***, ***Maarten Afschrift*** *and 1 anonymous reviewer*

Charlotte Le Mouel (2025) Improved accuracy of the whole body Center of Mass position through Kalman filtering. bioRxiv, ver. 3, peer-reviewed and recommended by Peer Community in Health and Movement Sciences.
https://doi.org/10.1101/2024.07.24.604923

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Estimation of the whole-body center of mass (CoM) is crucial in many biomechanical studies of human and animal movement. It is especially important in studies on the control of balance. For example, it has been assumed that sensory information is used to correct the horizontal position and velocity of the CoM (van Dieën et al., 2024; Wang and Srinivasan, 2014; Welch and Ting, 2008), to stabilize standing and walking against gravity. The studies cited have used more-or-less sophisticated estimates of the CoM, derived from kinematic, in some cases combined with anthropometric data, to predict motor outputs. These studies have provided support for the notion that the position and velocity of the CoM are controlled. This holds promise for the diagnosis of the quality of such feedback control as a cause of balance impairments and fall risk. However, such applications will suffer from errors in outcomes at the individual level, for example due to a poor fit of the anthropometrical model to a certain individual. Le Mouel (Le Mouel, 2025) presents a novel approach to estimate the position of the CoM. The author proposes that CoM estimation can be improved by optimally combining kinematic and kinetic data through a Kalman filter. The Kalman-filter-based method was indeed shown to effectively addresses the inherent limitations of both kinematic and kinetic methods used in isolation. The author used an innovative approach to validate CoM estimates, based on incorrect CoM estimates violating Newton's laws of motion. The new method substantially reduced errors compared to conventional approaches based on kinematic (and anthropometric) or kinetic data only. The paper presents a clear and comprehensive description of the method and code implementation is provided such that the method can be easily adopted by colleagues in the field. The author also shows how the new method improves the analysis of stabilizing feedback control of walking, demonstrating the promise it holds for the analysis of balance control. The method was tested on a small data set and further testing, preferably with participant pool showing large variance in anthropometrical properties, seems warranted. This may also lead to further improvement of the approach. For example, the anthropometrical model used could be refined by using regression equations that take into account segment circumferences of the individual tested (Zatsiorsky, 2002) or even by using individual imaging data. However, the proposed optimal combination of kinematic and kinetic data is likely to become a cornerstone of future methods for accurate CoM estimation.

References

- Le Mouel, C., 2025. Improved accuracy of the whole body Center of Mass position through Kalman filtering. bioRxiv, ver.3 peer-reviewed and recommended by PCI Health & Movement Sciences. https://doi.org/10.1101/2024.07.24.604923
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Reviews

Evaluation round #2

DOI or URL of the preprint: https://doi.org/10.1101/2024.07.24.604923
Version of the preprint: 2

Authors' reply, 07 January 2025

Dear Reviewer,

Thank you for your comments.

In the Methods, lines 268 - 272, I have added an explanation as to why the discrepancy between kinematic and kinetic positions is calculated over the average rather than a single gait cycle: "As mentioned in the introduction, calculating the CoM position from double integration of the force is highly sensitive to the integration constants used. To mitigate this problem, the CoM trajectories were calculated over an average gait cycle rather than a single gait cycle, and the integration constants were chosen so as to impose periodicity of the average trajectory."

I hope this clarifies the rationale behind this choice.

Best regards,

Charlotte Le Mouel

Decision by Jaap van Dieen, posted 20 December 2024, validated 20 December 2024

Dear Dr Le Mouel,

As one of the reviewers declined to review the revised version of your paper, I have invited a new reviewer. As you will see this reviewer is happy with the paper and has one suggestion for further improvement that I would ask you to take into account.

Best regards,
Jaap van Dieen

Reviewed by Maarten Afschrift, 20 December 2024

The paper presents a clear and comprehensive description of a Kalman filter-based method to enhance the estimation of center of mass kinematics. The core concept of the method is that center of mass estimated derived from rigid-body models and motion capture violate Newton's laws of motion, which can be solved by optimally combining measured external forces and kinematics. The inclusion of code implementation and the demonstration of the method's impact on foot placement control analyses are highly appreciated. I have one minor comment/suggestion regarding the methods section:

In lines 265–276, the authors describe a method to compute the discrepancy between kinematic and kinetic positions over a gait cycle. Could the authors clarify why this analysis was conducted for an average gait cycle rather than for each cycle individually? Addressing this point would help readers understand the rationale behind this choice and its implications for the analysis.

Evaluation round #1

DOI or URL of the preprint: `https://doi.org/10.1101/2024.07.24.604923`
Version of the preprint: 1

Authors' reply, 30 October 2024

Download author's reply

Decision by Jaap van Dieen, posted 17 September 2024, validated 17 September 2024

Dear Dr Le Mouel,

Two reviewers have assessed your preprint. Both see merit in the method developed. One of the reviewers has only limited comments, the other provides more substantial recommendations for a revision. I hope you can take these comments on board to submit a revised version of the paper.

Best regards,
Jaap van Dieen

Reviewed by Guillaume Durandeau, 07 September 2024

The paper present the use of Kalman filter to estimate the COM. The method is compared to model based methods and validated against the the COM acceleration during the flight phase of running.

Overall the paper is clear and complete.

I only have small comments:

1. The use of kalman filter method should be added to the title and abstract. Optimal merging, for me, recall more optimization methods than kalman filter.
2. In the methods section, it's not clear how the model were personalized.
3. In table 3, it's not clear if the data is in meters or mm. It's written in meters but then the percentage is with respect to something in mm.
4. Figure 3 and 4 have the same figure.

Reviewed by anonymous reviewer 1, 13 September 2024

The manuscript presents a novel approach for determining the position of the whole-body center of mass (CoM) by combining kinematic and kinetic data through the use of a Kalman filter. The authors effectively address the inherent limitations in both kinematic and kinetic methods when used in isolation, proposing a solution that reduces errors in CoM estimation, especially during dynamic activities such as running. The study shows that the combination of kinematic and kinetic information can significantly reduce the error in estimating CoM positions, with the proposed method being applicable across different kinematic models. The paper is well-written and structured, with the problem statement clearly outlined and the methodology appropriately justified. The manuscript's integration of statistical methods, such as bootstrapping and the Mann-Whitney U test, shows a thoughtful approach to handling the small sample size.

Below you can find my detailed review of each section of the manuscript:

Title and Abstract:
- The title of the manuscript seems to clearly reflect the topic of the manuscript.
- The abstract summarizes the key findings, including the error reduction achieved with the Kalman filter method, and clearly communicates the study's contributions.

Introduction:
- The introduction outlines the challenges in CoM estimation and proposes combining kinematic and kinetic data to improve accuracy. The hypotheses are logically presented.
- The literature review presented in the introduction, addresses the different types of CoM estimation methods properly, however, it comes to my concern that among the "Kinetic" methods the "LowPass filtering of the Center of Pressure" method (Caron et al., 1997), was left unmentioned. Moreover, a relatively recent and popular CoM estimation technique named "Statically Equivalent Serial Chain" (Cotton et al., 2009) was also left unmentioned in the literature section. This technique also utilizes both kinetic and kinematic information for CoM estimation. I would recommend this section to be modified accordingly.

Methods:
- The methods are detailed enough, including the use of a publicly available database and clearly defined protocols for data processing and analysis.
- Regarding the sample size, this can be considered a major limitation for this study (as mentioned in the limitation section), as only using 2 subjects, cannot reflect the generalizability of the study, I strongly recommend increasing the number of the participants (could be through incorporating data from another dataset).
- Regarding the statistical analysis, the use of Mann-Whitney U test and bootstrapping for confidence intervals, are appropriate and described in detail. Although the study could benefit from a larger sample size for more robust conclusions, there is no mention of a formal power analysis, which is typically used to determine whether a study has sufficient sample size to detect meaningful effects.

Results:
- The results are correctly described and interpreted. They support the hypothesis that combining kinematic and kinetic data reduces error in CoM estimation.

Discussion:
- The conclusions are supported by the results and do not overstate the findings. The author does acknowledge the need for further research to validate the method with larger datasets. However, the discussion could have been more focused on the practical implications of the proposed method. For instance, how could this Kalman filter-based approach be integrated into existing motion capture systems? How would it improve upon current methods in clinical gait analysis or athletic performance monitoring? The study would benefit from more concrete examples or applications.
- Another concern which should be pointed out, is that the study focuses heavily on the use of a Kalman filter to combine kinematic and kinetic data, without exploring alternative filtering or data fusion techniques. The assumption of linearity and Gaussian noise makes the Kalman filter suboptimal for handling non-linear

dynamics or complex noise models, which may be more prevalent in biomechanical data. The author could have explored or at least discussed other potential methods.

- Moreover, the lack of direct ground truth for horizontal CoM Coordinates should also be emphasized. Although the GRF are regarded as almost ground truth, it should be mentioned that it is still not optimal.

Summary of the review:

While this study provides an innovative solution to the problem of CoM estimation by combining kinematic and kinetic data through a Kalman filter, there are several areas where the work could be significantly improved. The small sample size, assumptions about Gaussian noise, and lack of exploration of alternative methods weaken the overall rigor of the study. Additionally, more discussion around computational complexity and practical applications would greatly enhance the manuscript's relevance. Addressing these points would result in a more robust, generalizable, and practically useful contribution to the field, otherwise this manuscript wouldn't be ready for publication.

Minor comments:

- Line 44: Please mention a reference for this statement "with an accuracy typically within 1 % of the person's weight".
- Line 156: "A few short gaps ...", I would advise to be more specific about the number/frequency of gaps available in the dataset.
- The manuscript would benefit from a thorough language revision to improve clarity and readability.