biomechanics

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A Comparison Between the Use of an Infrared Contact Mat and an IMU During Kinematic Analysis of Horizontal Jumps

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Abstract: Background/Objectives: This study compared step-by-step kinematic measurements from an infrared contact mat (IR-mat) and an inertial measurement unit (IMU) system during bounding and single leg jumping for speed, while also evaluating the validity of algorithms originally developed for sprinting and running when applied to horizontal jumps. The aim was to investigate differences in contact times between the systems. Methods: Nineteen female football players (15 ± 0.5 years, 61.0 ± 5.9 kg, 1.70 ± 0.06 m) performed attempts in both jumps over 20 m with maximum speed, of which the first eight steps were analysed. Results: Significant differences were found between the systems, with the IR-mat recording longer contact times than the IMU. The IR-mat began and ended its measurements slightly earlier and later, respectively, compared to the IMU system, likely due to the IMU's algorithm, which was developed for sprinting with forefoot contact, while more midfoot and heel landing is used during jumps. Conclusions: Both systems provide reliable measurements; however, the IR mat consistently records slightly longer contact times for horizontal jumps. While the IMU is dependable, it exhibits a consistent bias compared to the IR mat. For bounding, the IR mat begins recording 0.018 s earlier at touch down and stops 0.021 s later. For single leg jumps, it starts 0.024 s earlier and ends 0.021 s later, resulting in contact times that are, on average, 0.039–0.045 s longer. These findings provide valuable insights for coaches and researchers in selecting appropriate measurement tools, highlighting the systematic differences between IR mats and IMUs in horizontal jump analysis.

Keywords: step kinematics; measurement accuracy; bounding; single leg jump

Academic Editors: Elissavet Rousanoglou, John Buckley and Alan Godfrey

Received: 6 January 2025
Revised: 11 February 2025
Accepted: 12 February 2025
Published: 2 March 2025

Citation: Johansen, B.; Neville, J.; van den Tillaar, R. A Comparison Between the Use of an Infrared Contact Mat and an IMU During Kinematic Analysis of Horizontal Jumps. *Biomechanics* **2025**, *5*, 14. https://doi.org/10.3390/biomechanics5010014

1. Introduction

In sports like horizontal jumping, spatiotemporal parameters are often used to identify different determinants for performance [1]. These parameters are important in various areas such as sports performance analysis, rehabilitation, and biomechanical research as they provide insights into both immediate performance metrics and long-term development trends [2,3]. Horizontal jumps, such as bounding and single leg jumps (plyometric exercises), are widely used to develop explosive strength in participants of various sports [4–6]. There are many technologies that enable the measurement of step kinematics, such as high-speed cameras [7], force plates [8], 3D motion capture systems [9,10], inertial measurement units (IMUs) [11–13], and infrared contact mats [14–16].

To measure multiple horizontal jumps with 3D systems and force plates, expensive equipment and time-consuming setup procedures are needed. Moreover, specialized expertise and access to high-performance laboratories are often required to conduct accurate analyses. In contrast, infrared mats or wearable inertial measurement unit (IMU) systems offer a feasible, user-friendly, portable, and cost-effective solution. An infrared optical contact mat creates a "carpet" of infrared light a few millimetres above the ground. When the light is interrupted, the unit records the timestamp of the event, allowing the calculation of both contact and flight times based on the differences between their timestamps. van den Tillaar [16] showed that the use of Optojump infrared contact mats for stride detection in sprinting was accurate compared to laser/IMU measurements, which is also supported by studies that have confirmed the high validity of OptoGait in spatiotemporal analyses [15,17]. Previous studies have validated the accuracy of the Optojump system against force plates and high speed cameras for sprint and jump kinematics [15,17]. However, in both these studies [15,17] the Optojump system was compared to a stationary system, such as a treadmill, or vertical jumps. Therefore, it is not known how accurate it would be for horizontal jumps. Moreover, van den Tillaar [14] found that the Musclelab infrared mat produces comparable kinematic measurements to Optojump during sprints. Based on this, it can be inferred that the Musclelab infrared mat provides measurements that are as accurate as those from force plates for sprinting. Similarly, the use of IMUs has been shown to reliably record stride patterns during walking, running, and sprinting [11,12,18,19]. In addition, van den Tillaar et al. [16] found that a laser gun combined with IMUs attached to each foot (Musclelab, Ergotest Technology AS, Langesund, Norway) can automatically detect accurate step-by-step kinematics comparable to those detected by force plates during high-speed sprinting. Therefore, it seems that contact mats and IMUs are systems that can accurately detect step kinematics during sprints. However, it has been established that differences in velocity and step characteristics are present between sprints and various horizontal jumps [20]. During sprint races, fast sprinters make first ground contact with the front part of the foot, reach over 10 m/s, and have contact times and flight times of around 0.1–0.12 s [4]. Bounding for speed has certain similarities to sprint running, including landing on the front foot, but involves somewhat lower speed and longer contact and flight times. Single leg jumps are relatively unlike sprint running, with the heel making first contact with the ground, speeds below 6 m/s, and contact and flight times closer to 0.2 and 0.4 s [4,21]. Due to these differences, the accuracy of new technologies with regards to the measurement of these kinematic variables must be investigated.

Therefore, the aim of this study was to compare measurements of step-by-step kinematics between infrared contact mat and an IMU during bounding and single leg jumps for speed. This study evaluates already-established algorithms, originally developed for sprinting and running, to investigate their validity and reliability when applied to horizontal jumps. Furthermore, we investigate whether measurements between the two systems are affected by different jumping tasks (bounding and single leg jumps).

2. Materials and Methods

2.1. Participants

Nineteen moderately experienced female football players (age 15 ± 0.5 years, body mass 61.0 ± 5.9 kg, body height 1.70 ± 0.06 m) from a local football club participated in this study. The participants, who were selected as part of a larger training study where this equipment was used to assess their performance, were familiar with the exercises, having practiced them for six weeks prior to the tests. The participants were fully informed about the procedures, the potential risks, and the benefits of the study, both in writing and orally. Written consent was obtained prior to all testing. Parental consent was obtained for all subjects The study was conducted following the latest revision of the Declaration of

Helsinki and approved by the Norwegian Agency for Shared Services in Education and Research (project number 225529).

2.2. Procedure

Participants carried out an individual warm-up, consisting of approximately 5 min of jogging, followed by 5 min of an injury prevention program [22] and two submaximal sprints. After completing the warm-up, the participants performed a series of maximum-effort jump trials over a distance of 20 m. This distance was selected to ensure that all phases of the jump sequence—acceleration and maximum velocity—were captured [23,24]. They were tested during the preseason preparation period, when they engage in extensive physical training, wearing their regular running shoes for plyometric exercises. All trials were performed indoors on a tartan running track. Each trial began from a standing position, with a self-selected stance (one foot in front of the other). The jump exercises were performed in the following order: bounding for speed, followed by single leg jumps for speed on the right and left leg. Each participant completed a total of six trials: two for bounding and two for each leg in the single leg jump condition. The recovery time between attempts was 2–3 min.

2.3. Measurements

Contact and flight time were both measured with an IMU and an infrared optical contact mat (Ergotest Technology AS, Langesund, Norway). The IMUs (Ergotest Technology AS, Langesund, Norway) consisted of a wireless 3-axis accelerometer (±16 g, accuracy ±1.0%), a gyroscope (2000 deg/s, accuracy ±1.0%), and a magnetometer (±1300/2500 µT, accuracy ±5%), with a sampling frequency of 200 Hz and a weight of 20 g, fixed to the dorsal side of each foot with tape. The calculations of contact time and flight time with the IMU were determined by recognizing the velocity pattern of the plantar flexion/extension of both feet (Ergotest Technology AS, Langesund, Norway). The algorithm used to detect touch down and take off was originally developed for sprinting and running, where forefoot landings dominate. The infrared optical contact mat is composed of two 2.5 cm thick and 0.87 m long units ("master and slave") with a sampling frequency of 1000 Hz that were positioned at the start and end of the 20 m long test area. These units create a "mat" of infrared light approximately 5 mm above the floor, and breaks in this light (when the foot makes contact with the ground) are registered to record contact and flight times. Each participant's horizontal displacement was recorded with a laser gun (Noptel Oy, Oulu, Finland) directed towards their back during the tests. The laser gun continuously records distance over time using a CMP3 distance sensor (Noptel Oy, Oulu, Finland), sampling at 2.56 KHz. Horizontal speed was calculated using the distance over time during contact time with the laser. All recordings with the different sensors were synchronized and processed using Musclelab version 10.200.90.5095 (Ergotest Technology AS, Langesund, Norway).

Step-by-step analyses were performed on the first eight steps of each jump exercise, as this was the minimum number of steps completed by all participants. For each step, horizontal velocity and contact time were analysed using the IMU and IR mats. These parameters were automatically calculated by the Musclelab system for both measuring tools (Ergotest Technology AS, Langesund, Norway) and were earlier validated as very accurate in sprint step-by-step comparisons [14,16]. In addition, we examined the difference in total contact time, as well as the difference in the times when the foot hit the ground (touch down) and left the ground (take off). Flight times were not analysed, as they are the inverse of contact times when analysing absolute time measurements and, therefore, do not provide additional information about the differences between the two systems. Step length and frequency were also not analysed as these are directly related to the contact times and evt. differences would directly influence these parameters

2.4. Statistical Analysis

The data were tested for normality with the Shapiro–Wilk test and it was found that all data were normally distributed. To evaluate the validity between the two measurement devices and the two types of jumps, we performed two 2 (measuring device: IMU vs. IR mat/jump type: single leg jumps and bounding) × 8 (steps) ANOVA analyses with repeated measures. The first analysis compared the step velocities between the two jump types (single leg jumps and bounding) across eight steps. The second analysis evaluated the total contact times measured by the two tools (IR mat and IMU) over the same steps. Furthermore, a one-way ANOVA with repeated measures was performed on the differences in contact time between the two systems at touch down and take off for the eight steps. Where the sphericity assumption was violated, the Greenhouse–Geisser adjustments of the *p*-values were reported. The level of significance was set at $p < 0.05$. When significant differences were observed, post hoc comparisons were performed after Holm–Bonferoni correction. The effect size (Eta partial squared) was evaluated where $0.01 < \eta^2 < 0.06$ constitutes a small effect, $0.06 < \eta^2 < 0.14$ a medium one, and $\eta^2 > 0.14$ a large effect [25]. Bland–Altman analysis was used to examine systematic differences between the IR mat and IMU for touch down and time across different steps and velocities. Mean differences (systematic bias) and 95% confidence intervals were calculated and plotted as a function of speed. Regression analyses were performed to assess heteroscedasticity in the measurement differences. All data analyses were performed using JASP v. 0.17.3 (University of Amsterdam, Amsterdam, The Netherlands). Data were presented as means and standard deviations (SD).

3. Results

A significant effect of jump type ($F = 230$, $p < 0.001$, $\eta^2 = 0.45$), * steps ($F = 136$, $p < 0.001$, $\eta^2 = 0.36$), and jump type*steps interaction ($F = 25.7$, $p < 0.001$, $\eta^2 = 0.07$) was observed on step velocity, in which step velocity in during bounding increased significantly faster and longer than in single leg jumps and thereby resulted in significantly higher step velocity over the eight steps. In addition, one-way ANOVA with repeated measurements showed a significant effect of steps on speed for single leg jumps ($F = 15.655$, $p < 0.001$, $\eta^2 = 0.495$), and a significant effect was also observed for bounding ($F = 339.954$, $p < 0.001$, $\eta^2 = 0.955$), indicating a larger effect size for bounding (Figure 1).

When analysing the total contact times for each of the jump types between the two measuring tools, we found that significant effects on both types of jumps were caused by the measuring tool ($F \geq 415$, $p < 0.001$, $\eta^2 \geq 0.44$), steps ($F \geq 23.3$, $p < 0.001$, $\eta^2 \geq 0.43$), and measuring tool*steps interaction ($F \geq 2.7$, $p < 0.001$, $\eta^2 \leq 0.44$). Post hoc comparison reveals that contact times were consistently longer when measured with the IR-mat compared to the IMU. Furthermore, contact times decreased in both types of jumps, but the decrease over the steps was larger when measuring with the IMU compared to the IR-mat, especially in bounding. The analysis of total contact time confirmed this: for the IR-mat there was a significant effect ($F = 49.376$, $p < 0.001$, $\eta^2 = 0.755$), and for the IMU the effect was even greater ($F = 75.328$, $p < 0.001$, $\eta^2 = 0.825$). This indicates that both methods recorded a significant reduction in contact time over the steps, with the IMU recording greater changes overall. (Figure 2).

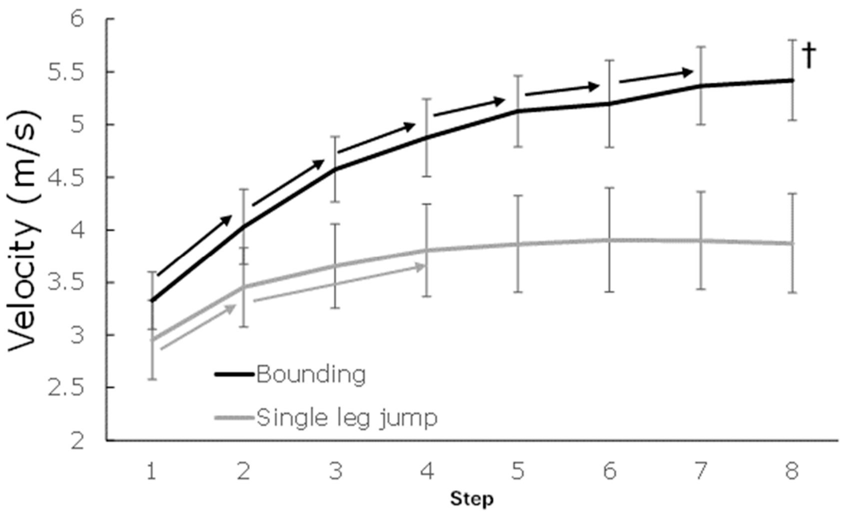

Figure 1. The mean (±SD) step velocity for bounding and single leg jumps measured with an IR-mat and a laser gun. † indicates a significant difference between the two types of jumps for all steps, → indicates a significant difference in velocity between this step and everything to the right of the arrow.

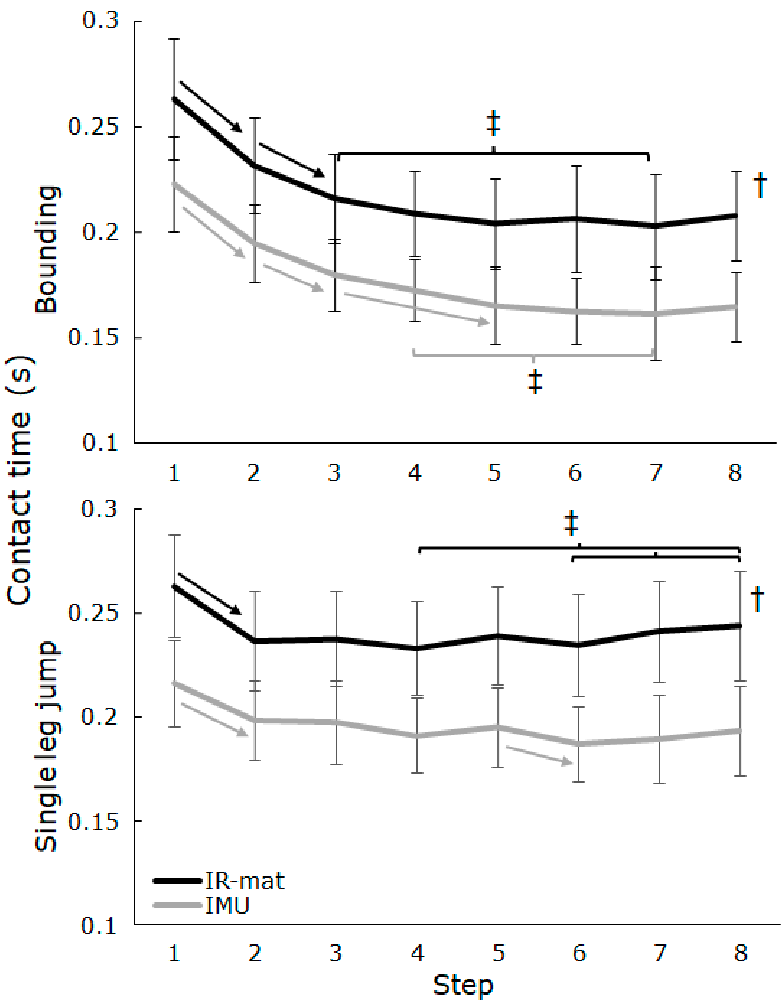

Figure 2. The mean (±SD) total contact time per step for bounding and single leg jumps measured with an IR-mat and an IMU. † indicates a significant difference between the IMU and the IR-mat for all steps, ‡ indicates a significant difference between these two steps for this measuring tool, and → indicates a significant difference between this step and everything to the right of the arrow.

The effect of velocity on the differences between the two systems was investigated using Bland–Altman plots, which evaluated the differences at touch down and take off. A systematic bias was identified: the IR mat consistently recorded an earlier start time for contact compared to the IMU at touch down, while it measured a later time at take off. This is reflected in the average bias: −0.018 s at touch down and 0.020 s at take off for bounding, and −0.024 s at touch down and 0.021 s at take off for single leg jumps (Figure 3). However, no significant effect of velocity ($r \leq 0.52$, $p > 0.05$) was found between these differences in times.

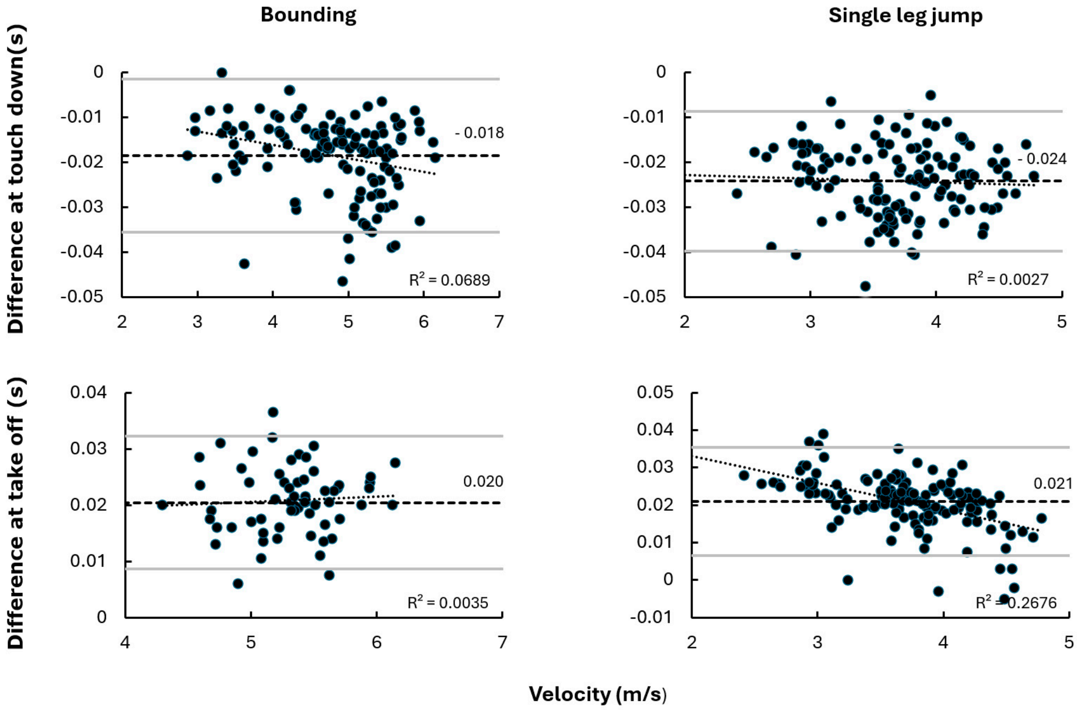

Figure 3. Bland–Altman plots showing the differences between the systems in regard to the time of touch down and take off (IR mat minus IMU, seconds) as a function of speed (m/s) for bounding and single leg jumps. Positive values indicate a longer time for the IR mat, negative values indicate a longer time for the IMU. The dashed lines show the average difference (systematic bias), while the solid lines represent 95% confidence intervals. Regression lines and R^2 values are included.

4. Discussion

The aim of this study was to compare step-by-step measurements from an IR-mat and an IMU during bounding and single leg jumps for speed. The main findings show significant differences between the two measurement systems in terms of total contact time, touch down, and take off.

Bounding jumps had the highest speed and the shortest contact time, in agreement with Mero and Komi [4]. Furthermore, we saw that the speed increased while contact time decreased throughout bounding, while for single leg jumps, we saw that this fluctuates more. This may be explained by the greater variability in landing patterns and the increased demands for balance and coordination in single leg jumps, which are inherently more complex exercises [12,15]. This study showed that the IR-mat consistently recorded a longer contact time compared to the IMU system. Previous studies have shown that IR-mats and IMUs are accurate in detecting contact time during sprint running, with only a minor difference of 0.003–0.004 s compared to a force plate [14,16]. From these studies, an algorithm to detect ground contact using an IMU was developed, in which an abrupt dip in angular velocity measured with the gyroscope together with a sudden acceleration spike were used to detect touch down and take off [14]. However, while sprinting a runner lands on their forefoot, while during bounding and single leg jumps they land on their heel [4]. This difference in landing pattern may contribute to the observed measurement differences, as the IMU pattern that identifies the touch down and take off through acceleration and angular velocity may perform differently with heel-based contact. Due to the mechanics of the heel-first landing, the back of the shoe, which has considerably more cushioning, will land first. Due to the shock absorption of the cushioning of the shoe, the IMU may detect the impact later than during sprint steps, in which athletes use spikes with much less cushioning and land on their mid/forefoot. This effect is further compounded by the location of the IMU, which is attached to the top of the shoe, which may result in slightly different IMU features.

The second factor contributing to the difference is the fact that the IR-mat starts to register foot contact approximately 5 mm above the ground. This setup means that it detects the foot slightly before touch down and stops recording a little after take off from the ground. Despite minor differences in the foot configuration at these points, the vertical speed at take off and touch down can be estimated using the following formula:

$$\frac{9.81^2 \times T}{2}$$

The average time in the air, measured by the IR-mat, was 0.198 s for bounding and 0.291 s for single leg jumps, which corresponds to vertical speeds at touch down and take off of 0.971 m/s and 1.427 m/s, respectively. The time it takes to move over 5 mm is calculated as follows:

$$t = \frac{d}{v}$$

For bounding this time is 0.005 s, while for single leg jumps it is 0.004 s. These differences explain only 15–25% of the variation between the two measurement methods, indicating that they cannot fully explain the observed deviations.

The third reason is the sample rate differences. The IR-mat records at 1000 Hz, while the IMU records at 200 Hz. In practice, this means that for each sample there is a maximum deviation of $\pm$0.005 s at touch down and take off.

Limitations and Future Studies

This study has some limitations that should be considered when interpreting the results. The participants were a homogeneous group of female football players with moderate experience in bounding and single leg jumps. Differences between the systems may arise when testing track and field athletes who are more experienced in these exercises and, therefore, may use different jumping techniques with higher velocities. Furthermore, the use of different footwear could lead to variations in landing and take off techniques, potentially influencing the results. This may limit the generalizability of the findings to other groups.

In addition, a gold standard, such as force plates combined with high-speed cameras, was not used, which prevents us from determining which system better aligns with the ground truth. Future studies should test both systems alongside force plates and high-speed cameras, with a broader range of athletes performing these types of jumps, to determine whether the observed differences are generalizable.

5. Conclusions

Our findings show significantly different measurements of contact times at touch down and take off between the IR-mat and the IMU in two different horizontal jump types. The IR-mat consistently recorded longer contact times by starting the measurements a bit earlier at touch down and ending slightly later than the IMU system at take off. The main reason for these differences is likely the fact that the algorithm for detecting touch down and take off was designed for sprint running and landing on the forefoot with sprint spikes, whereas the participants in this study landed on their heels and wore soft running shoes. Furthermore, the differences in sampling rate and the height of detection of the IR-mat may partially contribute to the differences in these parameters.

In practical terms, when choosing a measurement system for horizontal jumps, it is important to be cautious when comparing spatiotemporal parameters measured with different systems. IR-mats and IMUs differ in how they detect events like touch down and take off, with IR-mats recording these events directly and IMUs relying on algorithms. This can lead to variations, especially during heel-based landings in soft running shoes, highlighting the need for careful interpretation of results.

Author Contributions: Conceptualization: B.J. and R.v.d.T.; methodology: B.J. and R.v.d.T.; data collection and curation: B.J.; formal analysis: B.J. and R.v.d.T.; writing—original draft preparation: B.J.; writing—review and editing: R.v.d.T. and J.N.; visualization: B.J.; supervision: R.v.d.T. and J.N.; project administration: B.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Norwegian Center for Research Data approved 12 November 2021 (project number: 225529).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the national laws on privacy of the Norwegian government.

Conflicts of Interest: The authors declare no conflicts of interest.

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