

IMU- and TENS-based work and power calculation methods in hip flexion resistance training

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Purpose: The study is the first part of a series presenting the primary results of multijoint hip flexion resistance training biomechanical investigation. The series evaluates the exercise in the context of possible implementation in hip flexors shortening and hypertension. The described exercise was designed to use muscle hypertrophy as a solution for pelvis stabilizing muscles' imbalance. This study aims to evaluate the work performed and power generated during hip flexion resistance training using two established methods and investigate the potential of IMU sensors as a cost-effective tool for measuring individual performance and progress in non-laboratory settings.

Methods: The study was conducted with the use of training equipment constructed according to patent P.435615 allowing for the application of downward directed force to feet while performing hip flexion. Thirteen healthy students (7 females and 6 males, body-height 176.00 ± 12.54 cm, body-mass 73.69 ± 18.08 kg, age: 21.77 ± 1.09 years) took part in the training session using three different additional loads (0, 2.5, and 5 kg). Techniques applied in the study included optical kinematics capture, strain gauges, and inertial sensors.

Results: The average work of (TENS/IMU) were 56.57 ± 12.00 / 58.13 ± 13.07 - 76.54 ± 13.88 / 74.40 ± 13.93 J and an average power of 23.22 ± 6.43 / 23.65 ± 7.12 - 31.51 ± 9.42 / 31.62 ± 10.60 W were calculated for the additional load of 0 kg and 5 kg respectively. The correlation between values calculated with two tested methods was high both for power ($R = .85$ $P < .001$) and work ($R = .86$ $P < .001$).

Conclusions: Referenced data indicate a good correlation between the two methods but prove the need for further improvement of IMU-based method precision. It also allowed to determine a potential baseline of 15kg additional load for 1RM tests maximal value.

Keywords: imbalance, biomechanics, muscle, training, pelvis.

Introduction

Pelvis stabilizing muscles.

Muscle balance in the pelvis region is addressed by both sports and physiotherapy since the region is crucial for proper posture and motor system health. The scheme of hip flexors hypertension and shortening is commonly observed in sagittal plane posture defects¹ and chronic lower back pain symptomatic patients.² The main reason for such a correlation is the anatomically determined function of hip flexors (mainly iliacus, psoas major, psoas minor, tensor fascia latae, and gluteus minimus) and extensors (mainly gluteus maximus, biceps femoris long head, semitendinosus, piriformis, etc.). Psoas major attaches to the spine starting from the last thoracic to V lumbar vertebrae, passes the iliopubic eminence, and ends on the femur lesser trochanter. The psoas major shortening increases the compression forces in lumbar intervertebral discs and together with iliacus muscles increases the anterior pelvic tilt by decreasing the distance between its attachments.

The exercise of hip flexion resistance training has never been studied and its role in the pelvis region muscle balance is still unknown. The literature suggests that hip extension resistance exercise increases muscle imbalance measured by strength.³ The hips' range of motion was observed to change in the pre-season/season period in football players and the hip extension

presented lower values while in the state of high-intensity training.⁴ It suggests the measured level of muscle imbalance in studied athletes increases throughout the season. While all athletes perform core exercises, lumbar spine issues and increased pelvic tilt are common and rise in severity with the training intensity⁵ and years of experience.⁶ The exercise of hip flexion resistance training uses the technique of exercise-induced muscle hypertrophy, specific to powerlifting and bodybuilding to reduce hypertension and expand the length of crucial hip flexors. The exercise is performed in a standing position and allows the application of a downward-directed near-vertical force to the feet while raising the knees alternately. The crucial active work is performed by hip flexors which act against the load attached to the feet. It was designed as a multijoint exercise that target mostly iliopsoas, gluteus minimus, gluteus medius, and tensor fascia latae and reduces the impact of rectus femoris and abdominal muscles in active contraction. The knee bending during the rise phase cause the rectus femoris and abdominal muscles to work in near-isometric conditions.

Work and power measurement.

Mechanical power in sports is a characteristic presenting a high variability both in methods of calculation and level of model simplification. In literature, power is used as a strength or performance measurement or the indication of energy expenditure characterizing muscle work in time. The choice of

technique depends strongly on sports discipline and the aim of the study.⁷ Metabolic changes may give some data on metabolic power and indicate a holistic performance in endurance training. The same technique in specific muscle performance progress measurement is too imprecise especially when considering the contribution of different parts of the body to global energy consumption.⁷ There are three other popular methods for power calculations. The most precise technique uses a full-body model in inverse dynamics modeling, allowing for the highest level of model complexity.⁸ However the method uses kinematic data from a motion capture system and requires specific laboratory conditions unachievable for multiple sports disciplines. The second method requires force and kinematic data and allows the calculation of power based on mechanical power definition as work performed in time and the work definition as a product of force along the displacement.⁹ Both concentric and eccentric movements are included in the calculation of this method. However, while the precision of the results depends on sensors quality, the final variable characterizes the whole muscle group with no indication of specific muscles contribution proportions. The last and most simplified method uses the general definition of work as the energy transfer. It may be used in sports when the kinetic or potential energy of a considered body is known.¹⁰ This method's inaccuracy derives mostly from not taking into account the work performed by muscles in active movement amortization, especially during landing in vertical movement.¹¹ Nevertheless, this method requires data that may be gathered with the least cost and in nonlaboratory conditions, which makes it worth implementing in commonly available equipment. The calculation requires data on displacement and moved object mass. This study aims to (1) evaluate the work performed and power generated during hip flexion resistance training using two established methods, and (2) investigate the potential of IMU sensors as a cost-effective tool for measuring individual performance and progress in non-laboratory settings.

Material and methods

Participants

The study was conducted under informed consent and with the approval of the Human Research Ethics Committee in the spirit of the Helsinki Declaration. 13 healthy individuals took part in the study (7 females and 6 males, height: 176.00 ± 12.54 cm, weight: 73.69 ± 18.08 kg, age: 21.77 ± 1.09 years). All participants were students who had never before performed hip flexion resistance training. Exclusion criteria comprised any type of diagnosed significant posture defects, any metabolic ailment that could manifest in muscle abnormal physiology, significant pain symptoms, and pregnancy. None of the participants was excluded from the study.

Design

The research was conducted as an observational cross-sectional study of untrained individuals.

Training

The training proposed in the study allows for multijoint hip flexors resistance training in standing position. It uses a resistance force attached vertically to the feet while lifting the knees alternately to the hip height. The equipment was custom-made according to patent P.435615. The frame with the load pin shares the rotation axis with the beams and transfers the load from the weight plates to the foot bindings. The construction allows the application of near-vertical downward directed force to feet while training. The exercise was performed with an additional load of 0, 2.5, and 5

kg. Each trial comprised at least 5 repetitions for each side with an average repetition frequency of 12 reps/min.

Measurements

To validate IMU-based methods, the optical motion capture system combined with strain gauges was used. The machine was equipped with two types of custom-made sensors. Strain gauges (based on the HX711 weight module, and Arduino Uno Rev3 - A000066, Arduino S.r.l., Monza, Italy) were installed on the back of the feet and under the feet (one under each forefoot and each backfoot) to measure the forces at the interface between the body and the device. IMU sensors (inertial measurement unit based on MPU-6050 3-axis accelerometer and I2C gyroscope, DFRobot, Pekin, China, and Arduino Uno Rev3 - A000066, Arduino S.r.l., Monza, Italy) were placed on both beams for movement angular measurement. The kinematics were recorded with the BTS Smart optoelectronic motion capture system (12 cameras BTS EVO-8 system with 2 BTS VIXTA HD-pro cameras, BTS S.p.A., Milanese, IT, Italy) with the use of a full-body Vicon marker setup modified by the addition of markers on the 5th metatarsal bone and a set of markers on the training equipment. Markers placed on the foot bindings near the ankle were used for this study. These markers' location was set as a point on the bindings at the transverse axis of the ankle around 5 cm (the thickness of the bindings at this point) in the lateral direction. A part of the material contains tensometry data on the left side only since a sensor failure occurred on the right side during the measurements. Incomplete or disrupted data were excluded from the analysis.

Data processing and synchronizing

All data processing and analysis were performed in RStudio (R, The R Foundation for Statistical Computing, Vienna, Austria). Forces measured on the back of the feet contained two components. Most of the force was generated by the pulling motion. The remaining part is derived from the interaction between the feet and the bindings and depends on feet dynamics during training and the fastening tightness. The pulling motion component was separated by taking positive values from the result of subtracting the values of forces measured under the feet from the values measured on the back of the feet. Motion capture and tensometry data synchronizing path comprised two stages. The primary fit was achieved by cross-correlation with the use of interpolated same-frequency (100 Hz) data on force pulling component and ankle kinematics for each side respectively. The second stage consisted of the calculated work maximized over the range of 1.01 seconds (101 samples range).

Work and power calculation methods.

The power generated during each repetition of the exercise was calculated with two different methods. The tensometry and kinematic data were used to calculate work and power using work defined as a product of force along the displacement. Work was calculated as a quotient of force and displacement (absolute value of vertical axis marker position change). The IMU angular data, beam length, and the weight of the equipment beam and frame with the applied load were used to calculate the work as a change of potential energy. Both methods were compared to determine the possibility of estimating the work and power changes with the training program progress with the use of IMU

$$W_{TENS} = \sum F_i \cdot S_i = \sum F_i \cdot |\Delta h_i|$$

W_{TENS} – work calculated with data from strain gauges (tensometry sensors)

F_i – momentary force

S_i – partial displacement

Δh_i – height partial change (marker location partial change in

the vertical axis)

$$W_{IMU} = \Delta E_p = M \cdot g \cdot h = (m_e + m_l) \cdot g \cdot r \cdot \sin \alpha$$

W_{IMU} – work calculated with data from inertial sensors

E_p – potential energy

g – standard gravity

M – mass calculated as an average of downward directed force measured by strain gauges placed in the bindings with the additional load applied, within the range of 0-30° of beam inclination, divided by standard gravity

m_e – equipment mass component

m_l – additional load mass component

r – equipment beam length

α – equipment beam maximal inclination angle during the training repetition

Statistical analysis

The average ratio between the summary work and power for each repetition calculated with two different methods was used to optimize IMU-based method accuracy. This operation reduced the impact of the eccentric work missing component in the IMU-based method. Work and power calculation methods results were compared with the use of correlation coefficient depending on data distribution normality (Pearson correlation for work and Spearman rank correlation for power). The methods were further analyzed for agreement and visualized with Bland-Altman plots both before and after average ratio optimization. The Bland-Altman plot was used as the most reliable graphical tool for two methods comparison. It allows to show the proportion between the two methods values average and the difference between

them. It provides information on whether the difference between the methods is constant or proportional to measured or calculated values. This distinction is crucial in the context of planning of the tested methods optimization. Methods sensitivity was verified by testing results distinctiveness between three different loads applied. Most of the data didn't fulfill the normality requirement for parametric statistical testing. Thus, the Kruskal-Wallis's rank sum test was used to determine the statistical significance of the difference between work and power calculated from data measured during the training with different loads. Statistical significance was considered for an alpha level of .05 for all statistical tests.

Results

In the studied exercise hip flexors muscles groups performed an average work of (TENS/IMU) $67.05 \pm 15.92 / 67.33 \pm 15.35$ J and generated an average power of $27.66 \pm 8.44 / 28.25 \pm 9.40$ W that varied depending on the applied load. The tens-based peak power was maximal for 5kg of additional load and reached the values of 78.34 ± 42.26 W for women and 89.62 ± 39.61 W for men.

The Bland-Altman plot of unoptimized data regression line inclination indicated an error proportional to the calculated values. The optimization performed with the use of the calculated average ratio (work: $\cong 1.173$ and power: $\cong 1.024$) reduced the average difference between related values and the regression line inclination for work results (Figure 1). Results calculated with two different methods for both work and power were highly

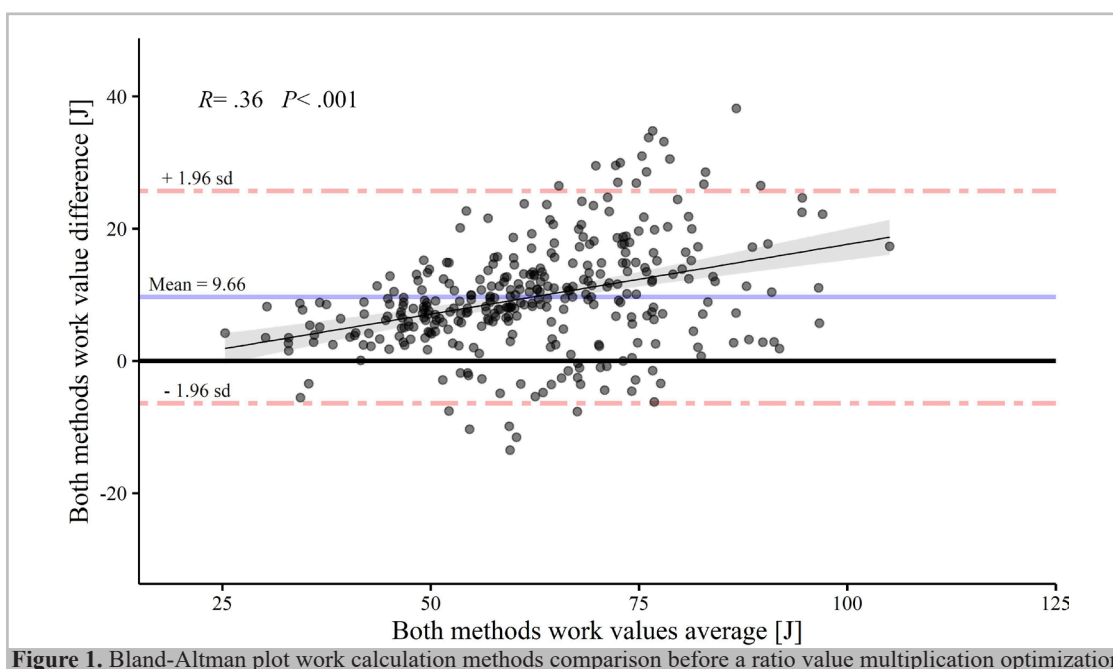


Figure 1. Bland-Altman plot work calculation methods comparison before a ratio value multiplication optimization

correlated (work: $R = .86$ $P < .001$, power: $R = .85$ $P < .001$). However, the methods didn't show complete interchangeability. The proportion ratio varied between participants and all exercise repetitions in the range of .80-1.59 for work and .53-1.53 for power. The results indicated the need to conduct further research to optimize power calculation methods in exercise biomechanics. Most of the data didn't fulfill the normality criteria required for conducting parametric tests. However, the differences between values calculated for different additional loads were statistically significant for most groups. Kruskal-Wallis tests showed significant differences between work and power values calculated for different loads with the use of the TENS-based

method. The IMU-based method didn't show a significant difference only for the comparison between power generated with the 2.5 kg and 5 kg plate load (Figures 2 and 3).

Discussion

A very good correlation between values calculated with methods confirms the possibility of using both methods for the rough estimation of work and power. However, these results confirm the method based on energy transfer lacks precision in vertical resistance training and generates underestimated values. The

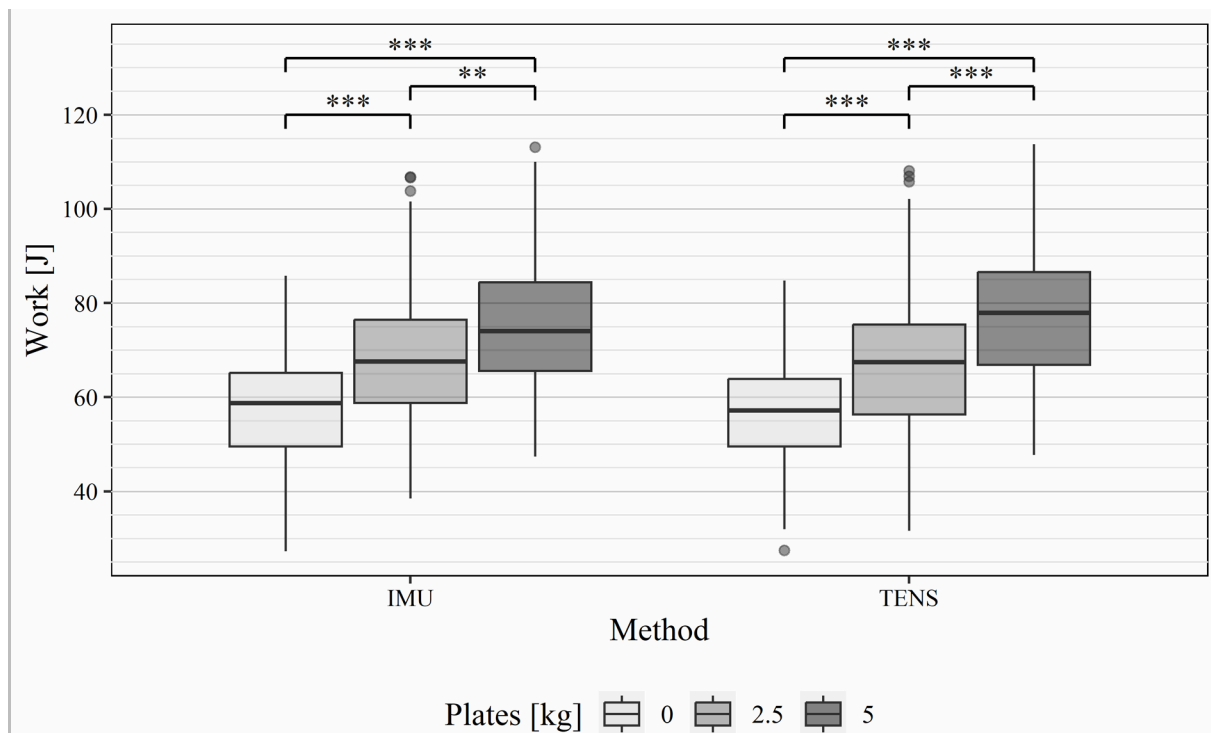


Figure 2. Work performed during a single repetition calculated with both methods for three different additional loads, *** - $P < .001$, ** - $P < .005$, * - $P < .05$, ns - $P \geq .05$

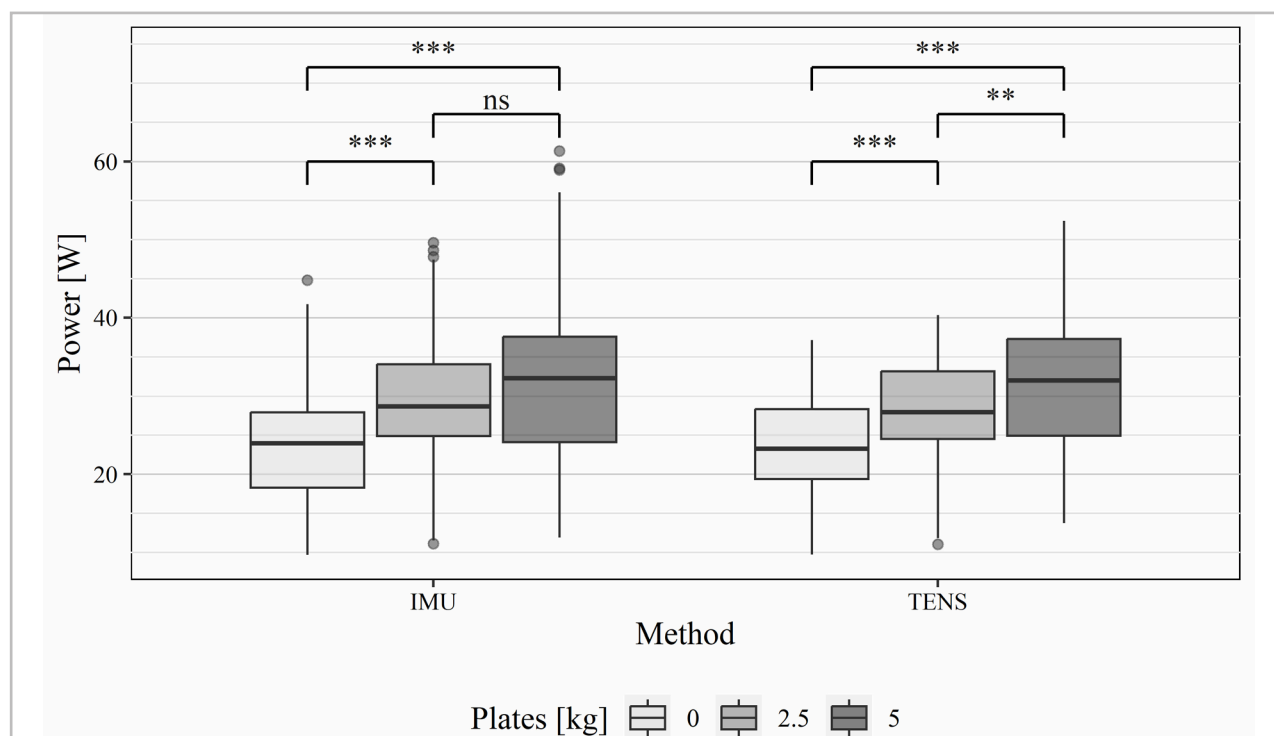


Figure 3. Power generated during a single repetition calculated with both methods for three different additional loads, *** - $P < .001$, ** - $P < .005$, * - $P < .05$, ns - $P \geq .05$

study brings preliminary data on differences between values achieved with both methods and allows planning of further work on the subject. Most literature indicates the source of divergence in the factor related to work performed in eccentric contraction¹¹. The issue has previously been studied and similar results have been shown. The proportion between real and calculated work and power may depend on multiple factors. In this study, the error between the used methods was partially proportional to the calculated values, and the use of an average ratio as a multiplying factor allowed for the reduction of the main part of the results divergence. The ratio in the form of a single value was used successfully for the studied participants but the group was characterized by a high homogeneity, especially considering the previous non-existing experience with the performed

exercise. Thus the simple ratio multiplication operation may be inapplicable to the general population and the multifactorial analysis is required to determine possible factors influencing the ratio intersubject and intrasubject variability. The eccentric part of the exercise can be performed with varying muscle involvement. Thus, factors such as exercise pace, and muscle activity in eccentric movement should be considered. The general muscle mass and current 1RM can also play a significant role.

While the strong significant differences between work calculated for each load provide evidence for method sensitivity, the power results are not equally obvious. Power is a characteristic that depends on the muscle's anatomy and physiology.¹² Its value is commonly used to determine muscles' performance potential.¹³

Power values for a specific exercise should rise with the load and reach a plateau of the current individual limit. It was also proven the peak power maximal values are usually reached for ~70% 1RM in untrained and ~50% 1RM in trained individuals.¹⁴ Within the studied group's average power, a decrease in the distinguishability of different loads was noticeable as low as for 2.5/5 kg. It allows to assume the 1RM will not exceed the additional load of 15 kg and the average peak power of 120 W. The data indicate the hip flexors' potential to be roughly at least 5 times lower than hip extensors' in the peak power test in two legs press of untrained subjects.¹⁴ The estimated 1RM value gives a baseline for future exercise studies. It allows to predict the range of loads that will be used in the training.

Practical Applications

The study shows a good correlation between the two methods of work and power calculation. It also confirms an IMU-based method allows for a rough estimation of the work done and the power generated during the resistance exercise of hip flexion without the need for professional biomechanical equipment. While the power values provide relatively reliable data, the work calculation process quality remains unsatisfying. Most importantly, the study provides primary information on performed work and generated power of untrained subjects during hip flexion resistance exercise. The exercise is physiologically new and requires more caution in implementation. The obtained results allowed to determine the possible value of additional load that will state a baseline for the 1RM measuring process in future studies. These results are an important element in building a methodology for measuring the effects of hip flexion resistance training implementation.

Conclusions

Inertial sensors can be implemented to measure power in exercise biomechanics. The IMU-based work calculation method requires more investigation. IMU-based power calculation method can be used to monitor hip flexion resistance training individual performance and progress. The hip flexion exercise 1RM testing protocol should be scaled for a maximal additional load of 15 kg.

Ethical Committee approval

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Topic

Sport Biomechanics.

Conflicts of interest

The study was conducted using specific training equipment protected by patent. However, the method described in the study does not require the exact machine. The corresponding author is the author of the training equipment used in the study, the owner of patent intellectual property rights as well as the owner of a company producing the equipment. The authors

declare no further conflict of interest.

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Author-s contribution

Conceptualization, D.F. and R.M.; methodology, D.F. and K.J-W; software, D.F.; validation, R.M.; formal analysis, R.M.; investigation, D.F. and K.J-W; resources, D.F.; data curation, D.F.; writing—original draft preparation, D.F.; writing—review and editing, R.M. and K.J-W; visualization, D.F.; supervision, R.M. and K.J-W.; project administration, D.F. All authors have read and agreed to the published version of the manuscript.

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