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RELATIONSHIP BETWEEN MINIMUM FOOT CLEARANCE, WAIST ROTATION AND AGING: TOWARD FALL PREDICTION AND PREVENTION

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Abstract: *The gait patterns of older adults were measured and analyzed to develop a practical device to reduce the risk of falls. The gait measurements were performed on healthy older adults (n=28) aged over 55 during usual walking using an optical motion capture system and an inertial measurement unit with a 3-axis gyro sensor and a 3-axis accelerometer placed on the hip over the sacrum. Various stages of gait patterns were investigated to estimate and compare participants' feet trajectories and body movements. Chronological age did not correlate with minimum foot clearance (MFC) during the swing phase (correlation coefficient, r=0.22, p>0.05) as an index of the risk of fall. Significant correlations were found between MFC and waist rotation along the rostro-caudal axis (yawing, r=0.40, p<0.05), between waist rotation and body mass index (r=-0.44, p<0.05), and between one-leg standing duration (OLSD) and waist rotation along the anterior-posterior axis (rolling, r=0.44, p<0.05). MFC and OLSD were not significantly correlated (r=0.16, p>0.05), suggesting their independence. Taken together, these observations suggest that a predictor of falls can be formed based on individual gait patterns, waist and upper body movements, and overall physique, in addition to aging and associated muscle weakness. In a follow-up study (n=40), two more sensors were placed on the insteps and the observations were successfully replicated. The MFC and mean absolute error (MAE) between the measured (motion capture) and estimated (sensor) trajectories showed significant agreement (r=0.73, p<0.05, MAE = 0.071 ± 0.069 [standard deviation] for the left foot; r=0.66, p<0.05, MAE = 0.072 ± 0.072 for the right foot). These results provide potentially novel characteristic data indices for biomechanical gait analysis, thus contributing to fall prediction and potentially leading to new techniques required for the implementation of fall prevention devices.*

1 INTRODUCTION

Preserving mobility is an essential issue for lifelong healthcare [1]. Elderly falls and subsequent immobilization lead, in the worst cases, to the reduction or loss of physical, mental, and social activity and functionality, which cannot be easily restored though rehabilitation after the incident. Prevention or reduction of the risk of falls is desirable and should lead to a better quality of life.

In contrast to the apparent ease of the performance, human bipedal walking is based on highly complex neural and musculoskeletal coordination and control of the lower limbs. In the biomechanics field, computational modelling of bipedal walking using computer simulation or robotic implementation remains too immature to cover the broad range of gait pattern spectra, spanning from normal to pathological cases. While there are a number of clinical observations and statistically or empirically derived behavioral indices for evaluating the deterioration of gait patterns (e.g., walking speed) [2] and their physiological interpretations, there are limited reports from the computational kinematics perspective.

Recent technological developments appear promising in their ability to advance the prediction and prevention of falls. Specifically, inertial measurement units enable the practical measurement of activities of daily living, including walking outside of the laboratory, in place of traditional methods such as optical motion capture systems and force plates [3].

In this vein, the ultimate goal of the present study is to apply a novel computational engineering perspective to develop a practical device for reducing the risk of falls in older people. As the initial step, here we report our conceptual and technical framework: the relationship between minimum foot clearance, waist rotation, and aging, and their measurement by inertial measurement units (sensors).

2 METHODS

2.1 Participants

Community-dwelling older adults participated in the first and follow-up studies conducted in March 2016 (n=28, age range:55–75, 13 females) and March to December 2017 (n=40, age range:57–83, 18 females), respectively. The inclusion criteria were i) residence in Wako, Saitama Prefecture, Japan, and ii) sufficient physical health to be able to visit the measurement site in the city without a caregiver’s support, and sufficient mental health to provide informed consent to participation and perform the required tasks. The exclusion criteria were any signs of neurological, psychiatric, epileptic, or cardiovascular diseases, seizure at the time of measurement or in the past, or infection at the time of measurement. The studies were approved by the institutional review board and written informed consent was obtained from individual participants in advance.

2.2 Apparatus

Walking gait was measured using an optical motion capture system (Optitrack Motive, NaturalPoint Inc., Corvallis, OR USA). Markers were placed on 41 locations on the body including the left and right insteps and captured by 16 infrared cameras. Six-axial (3 gyro-sensors and 3 accelerometers, TSND121, ATR-Promotions, Kyoto, Japan) sensors were put on the hip over the sacrum in the first study, and additionally on the left and right insteps in the follow-up study. A set of eight force plates (Sports-Sensing, Fukuoka, Japan) arranged in a 3-m-long row was also used in the follow-up study. Height and body weight were measured with a height and weight scale.

2.3 Measurement

The participants were instructed to walk at their usual speed in the experimental room. They walked back and forth several times while their gait patterns were recorded with the optical motion capture system and sensors. The walkway was approximately 3 m long and was marked on the floor in the first study (Figure 1), and defined by the force plates in the follow-up study. One-leg standing duration (OLSD) was measured manually using a stopwatch.

The optical motion capture system sampled the data points at 100 Hz in both studies, and was synchronized with the force plates in the follow-up study. The sensors sampled the data points at 500 Hz in both studies.

Figure 1: Measurement set-up in the first study

2.4 Data Analysis

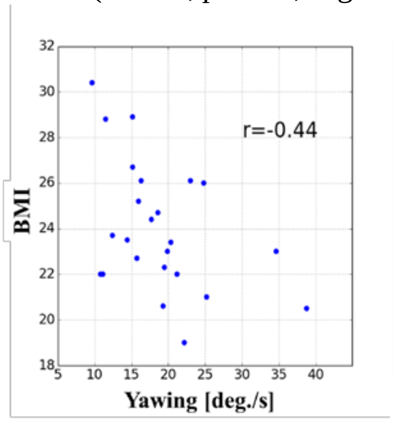
Feet trajectories were derived directly from the motion capture data in the first and follow-up studies. They were additionally estimated from the instep sensor data using in-house software in the follow-up study. The software was based on a proposed algorithm [4] and transformed the measured data represented by the sensor-based coordinate system into the world coordinate system, congruent with the motion capture system, by estimating the orientation time-series of the sensor from the angular velocity. After subtracting the gravity, the acceleration in the transformed coordinate system was integrated to calculate the three-dimensional position namely trajectory. Drifts were removed by re-setting the position and the velocity for each foot-flat period, defined in terms of the empirically-derived thresholds of the norm of the acceleration. A few other signal processing techniques were introduced for more accurate estimation.

Minimum foot clearance (MFC), the minimum distance between the height of the foot and the floor during the swing phase, was estimated for individual steps, assuming two peaks and one valley during the swing phase and averaged for individual feet. To measure waist rotation, the yawing (WRY) and rolling (WRR) angular velocities were estimated from the waist sensor data.

The relationships among the MFC, chronological age (CA), body mass index (BMI), OLSD, WRY, and WRR were evaluated by Pearson correlation coefficients. Agreement between the MFC obtained from the optical motion capture and that estimated from the sensor was evaluated by the mean absolute error (MAE).

3 RESULTS

In the first study, MFC showed a moderate positive correlation with WRY (r=0.40, p<0.05), but no significant correlations with CA (r=0.22, p>0.05) or OLSD (r=0.16, p>0.05). WRY was negatively correlated with BMI (r=-0.44, p<0.05, Figure 2). OLSD was positively correlated with WRR (r=0.44, p<0.05, Figure 3).



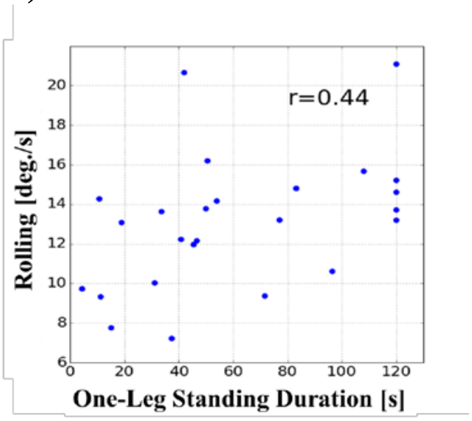


Figure 2: Yawing vs BMI   Figure 3: OLSD vs Rolling

In the follow-up study, while the same pattern of results was observed, only the negative correlation between WRY and BMI was significant (r=-0.38, p<0.05). There was a significant correlation between the measured (with optical motion capture) and estimated (with sensor) MFC (r=0.63, p<0.01, Figure 4). The MAE between the measured and estimated trajectories, calculated for the 23 (out of 40) participants with artifact-free reliable motion capture data, showed significant agreement (r=0.73, p<0.05, MAE = 0.071 ± 0.069 [standard deviation] for the left foot; r=0.66, p<0.05, MAE = 0.072 ± 0.072 for the right foot; see Figure 5 for an example).

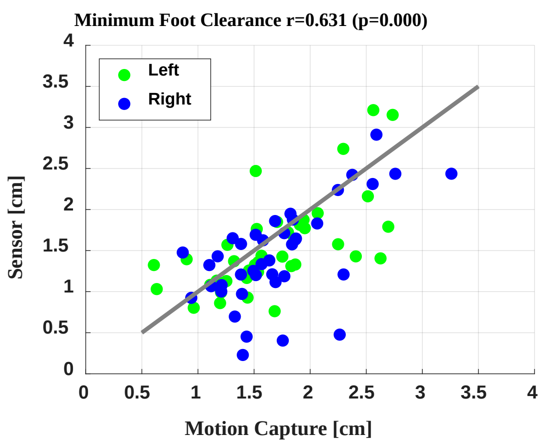


Figure 4: Agreement between motion capture and sensor-estimated MFC

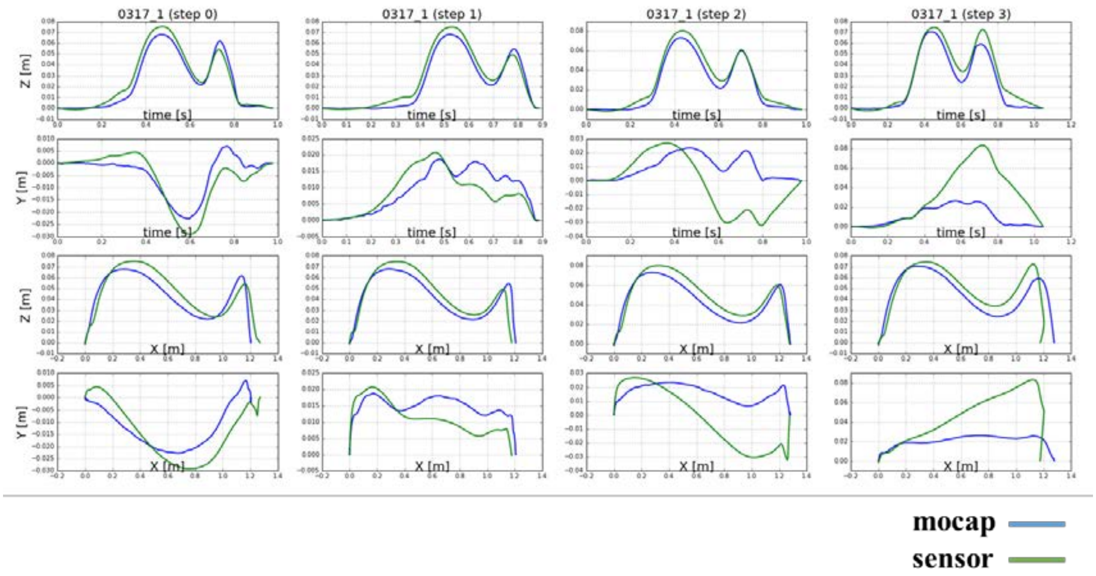


Figure 5: Comparison of the measured (motion capture) and estimated (sensor) trajectories

4 DISCUSSION

The results are summarized in Figure 6. They suggest that individual gait patterns, specifically MFC and waist rotation, in addition to aging and associated muscle weakness, can be used as predictors of falls.

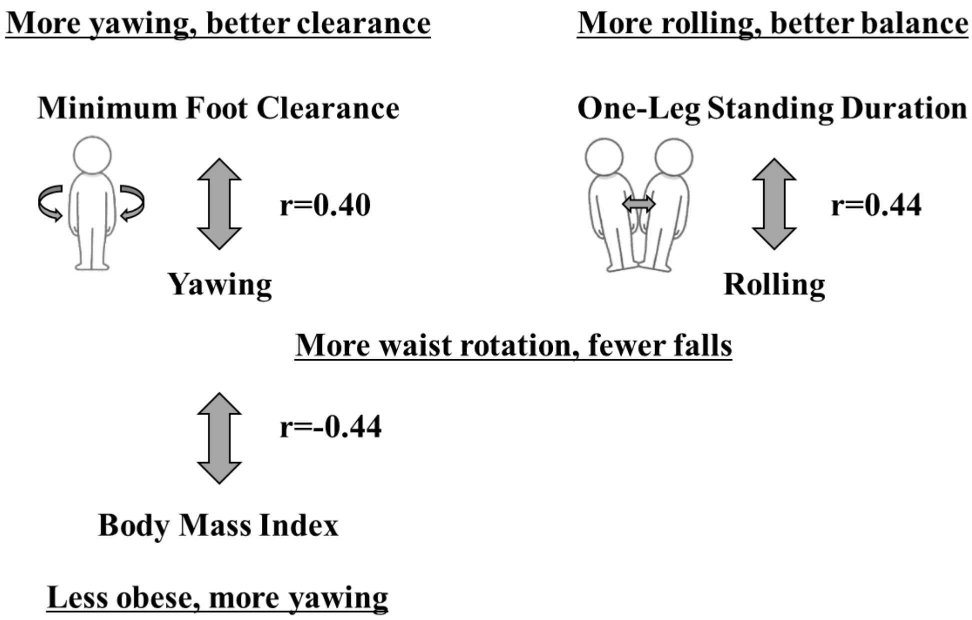


Figure 6: Summary of the findings

Gait and gait pathology are generally discussed in the context of lower limb functionality. In contrast, the present results suggest the importance of waist and upper body functionality.

More comprehensive kinematics may need to be developed to improve fall prediction and prevention.

The present results also indicate that the inertial measurement unit, or the gyro- and accelerometer sensors, may provide information that is directly related to the risk of fall, and thus may be suitable as a practical and relatively inexpensive device for use in daily situations.

There remain some reservations. Despite the increased number of observations, the follow-up study did not completely replicate the first study. Some improvements to the study protocol or data analyses, or revision of our viewpoint, may be necessary. Indeed, due to the limitation of our experimental setup, the present observations may not reflect the participants' natural gait. Measurements should be taken under a more natural setup in future studies. It should also be noted that due to the selection criteria, most of the participants did not show a high risk of falls. Consequently, it is unclear whether the alleged relation between waist rotation, MFC, and OLSD as indices of fall risk can be extrapolated from the normal gait variability to broader spectra covering more deteriorated or pathological cases. While it is clear that data from people with difficulty in walking are necessary, special care obviously needs to be taken with this population from both research and clinical viewpoints. Finally, while we may have added novel indices for the evaluation of fall risk, there are a number of other parameters that were not taken into consideration in the present study, such as temporal gait variability and cognitive impairments.

5 CONCLUSIONS

In this paper, we have reported our current conceptual and technical framework towards fall prediction and prevention. We have indicated the importance of yawing and rolling during waist rotation, as well as foot clearance, in biomechanical gait analyses and interventions in medical and sports sciences, and demonstrated the feasibility of measuring waist rotation and foot clearance with inertial measurement unit sensors in practice.

6 ACKNOWLEDGMENTS

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