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Development of Linear Regression Models to Estimate the Margin of Stability Based on Spatio-Temporal Gait Parameters

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ABSTRACT Spatio-temporal gait parameters such as step width, cadence, stride length, and walking speed contribute to dynamic stability. Several studies have investigated the role of gait parameters in maintaining balance. However, in these studies, subjects were instructed to alter their gait. This intentional alteration has the potential to create error in the results, as subjects are not walking with a natural and comfortable gait. In consideration of this, the sample chosen in this study consisted of patients who had undergone a knee replacement. Such individuals naturally have gait parameters that differ from normal subjects. The primary objective of this study was to develop regression models that predict and measure gait stability in both the anterior-posterior and medio-lateral directions based on gait parameters. The maximum deviation of the extrapolated center of mass from the border of the base of support was the measure of gait stability. A forward stepwise multiple regression analysis was conducted to develop both models. In testing the goodness of fit of models, the values of coefficient of determination, standard error of estimates, and root mean square error were calculated. Both models showed sufficient values of goodness of fit. To improve walking stability and minimize falls, fall-prone people should walk with an adequate base-of-support area, and with lower cadence and speed. The results of this study contribute to an understanding of gait patterns and their relationship to walking stability and to how gait strategies might be taught in physical therapy programs to minimize the risk of falls.

INDEX TERMS Base of support, cadence, extrapolated center of mass, gait, stability, step width, stride length, walking speed.

I. INTRODUCTION

Dynamic stability is required for the successful performance of a variety of activities of daily living. Gait instability is associated with a higher risk of falling [1]. Each year, millions of people experience a fall. A single fall doubles one's chances of falling again [2]. One out of five fall incidents causes a serious injury, such as head injuries or broken bones [3], [4]. Each year, 3 million elderly people are treated for fall injuries, with at least 300,000 people being hospitalized for hip fractures [5], [6]. More than 95% of hip injuries are caused by falling, usually by sideways falling [7], [8]. Falls are the most common cause of traumatic brain injuries [9]. In 2015, the total medical costs for falls totaled more than US $50 billion [10]. Some of the most important factors that contribute to a fall are difficulties in walking and maintaining stability.

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Therefore, there is a need to understand the contribution of gait parameters to the maintenance of walking stability. Several studies have examined the association between gait characteristics and stability [11]–[15]. In these studies, subjects were instructed to change their walking patterns in order to investigate how stability was affected. This has the potential to introduce experimental error, since these walking styles do not represent a natural and/or comfortable gait. For example, during steady state walking, individuals tend to select a consistent and comfortable speed, cadence, and base of support (BoS) area [16], [17]. Therefore, the sample chosen in this study consisted of patients who had natural but atypical walking patterns [18]. Patients who participated in this research had undergone knee replacement surgery with either an allograft or metallic replacement.

As with many human activities, locomotive stability control is a complex task that involves the coordination of nervous, sensory, and motor systems to regulate the body's center of mass (CoM) in a precise and efficient manner. Walking stability can be quantified by the ability to control the CoM movement relative to the BoS (which is defined as the area between and underneath both feet) in order to calculate the margin of dynamic stability (MDS) [19]. The latter is defined as the deviation between the extrapolated center of mass (XCoM; i.e., the CoM position extrapolated in its velocity) relative to the border of the BoS. In line with previous research, the MDS was measured in both medio-lateral (M/L) and anterior-posterior (A/P) directions using the lateral and front borders of the BoS, respectively [12]. Therefore, a large distance between the XCoM and the BoS is considered as an unstable condition.

The goal of this study was to build regression models that will predict gait stability in both directions (i.e., A/P and M/L) based on gait parameters. The results obtained from this study will help in predicting and measuring A/P and M/L walking stability based on gait spatio-temporal parameters without the use of advanced equipment and tools. Moreover, these results contribute to an understanding of the role of gait patterns in walking stability and how to apply gait strategies that might be taught in physical therapy programs to minimize the risk of falls. In this study, it was hypothesized that gait parameters such as walking speed, cadence, stride length, and step width would significantly predict gait stability in both directions.

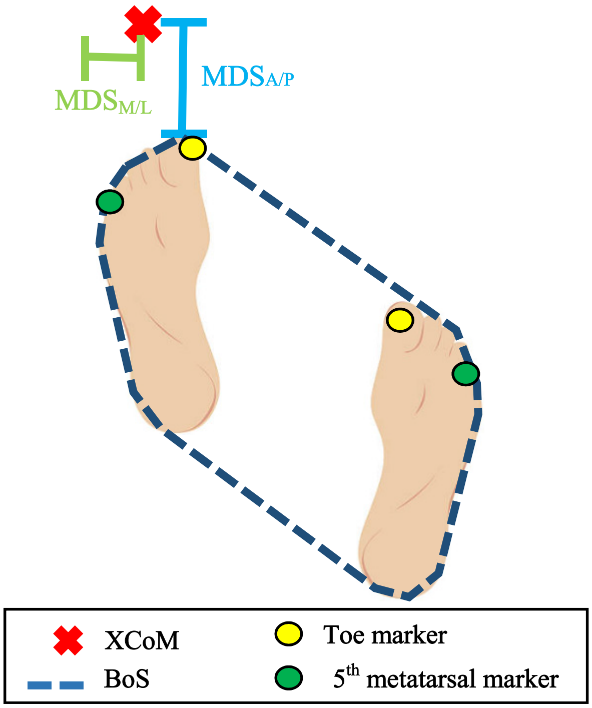

FIGURE 1. Margin of dynamic stability (MDS) in both directions (medio-lateral (M/L) and anterior-posterior (A/P)) during the double support phase (where COM is center of mass and BoS is base of support).

II. METHODOLOGY

A. QUANTIFYING GAIT STABILITY

Motion analysis was conducted using the Vicon's plug-in gait model (15-segment model) with 37 reflective markers attached to the entire body. This information was used to determine the body's CoM. In order to measure walking stability, the MDS in both directions (i.e., A/P and M/L) was calculated using the XCoM concept using a linear pendulum method. This method has been used in other studies on gait stability [20], [22]. The XCoM is the position of the CoM extrapolated in the direction of its velocity (refer to "Equ. (1)" below).

$$XCoM = CoM + \frac{V_{CoM}}{\sqrt{\frac{g}{l}}} \qquad (1)$$

where:

$XCoM$ is CoM extrapolated in the direction of its velocity,

V_{CoM} is velocity of the body's CoM,

g is acceleration due to gravity (9.81 m/s^2), and

l is the height of the body's CoM (usually equal to leg length).

The MDS describes the stability of a system as the maximum distance between both the anterior (i.e., forward) and lateral (i.e., sideways) borders of the BoS in relation with the position of the XCoM during the double support phase. The MDS was measured in the A/P and M/L directions, as shown in Fig. 1 (refer to "Equ. (2)").

$$MDS = max|BoS - -XCoM| \qquad (2)$$

where BoS is the base of support. During $MDS_{M/L}$, the 5th metatarsal reflective marker represented the lateral border of the BoS. In the $MDS_{A/P}$, the toe reflective marker served as the front border of the BoS.

B. MEASURING GAIT SPATIO-TEMPORAL PARAMETERS

A motion capturing system was used to measure the spatio-temporal gait parameters. These included stride length (defined as the length of two consecutives steps (cm)), walking speed (measured in meters per second (m/s)), cadence (expressed as steps per minute (steps/min)), and step width (defined as the distance between both feet (mm)).

C. PARTICIPANTS

Patients with malignant tumors of the distal femur who underwent wide resection and reconstruction of the distal femur participated in the study. Five patients had a metallic endoprosthetic replacement of the distal femur and five patients had allograft reconstructions of the bone. Five normal and healthy subjects participated in the study. During the metallic endoprosthetic replacement, the malignant tumors in the distal part of the femur, knee, and proximal area of the tibia were substituted with custom-made metallic parts. During the allograft reconstruction surgery, the malignant tumors were removed and the area was then reconstructed with allograft bones and knees from cadavers who had proximal anthropometric measurements. The demographics of the participants are shown in Table 1.

TABLE 1. Demographic information.

	Metallic	Allograft	Normal
No. of Subjects	5	5	5
Gender	4 males	4 males	5 males
Height (cm)	175.75 (± 8.49)	163 (± 8.01)	170.63 (± 1.53)
Weight (kg)	89.63 (± 15.46)	66.04 (± 8.27)	70.43 (± 4.21)
Age (years)	42.25 (± 5.9)	28.6 (± 5.6)	26.58 (± 0.97)
Side	2 right, 3 left	2 right, 3 left	-

D. EXPERIMENTAL PROTOCOL

The experiment was conducted at the Biomechanics Lab of the University of Miami. The experiment involved subjects walking at a self-selected walking speed along a 4 m walkway embedded with four force-plates (Kistler®, Winterthur, Switzerland). Participants walked normally more than ten times on the experimental area. The best six trials were then selected. A total of 90 trials were recorded. At a sampling rate of 120 Hz, motion data were captured and recorded via a Vicon® motion capturing system (Oxford Metrics, United Kingdom) with Nexus® software (version 2.5) and integrating ten cameras. Several other locomotion studies have used the same motion capturing system and software [23], [25]–[27]. The experimental protocol was approved by the Institutional Review Board (IRB) of the University of Miami. All participants received informed written consent prior to their inclusion in the study.

E. STATISTICAL ANALYSIS

The three groups were assessed for differences with respect to walking stability to assess whether the selected sample size was appropriate for the regression models. For this purpose, one-way analysis of variance (ANOVA) was used to test whether there was a significant effect of knee type on gait stability. This was followed by a Tukey's post-hoc analysis to detect any significant differences between the groups [28]. A forward stepwise multiple regression analysis was then used to determine if any gait spatio-temporal parameters such as step width, cadence, stride length, and walking speed could predict gait stability. Stepwise multiple regression analysis was used because it is important to include independent variables (i.e., gait parameters) that improve the model [15], [29]. To determine the level of collinearity, correlation coefficients were calculated between all independent variables. All results were considered to be significant at *p-value* <0.05. Backward stepwise analysis was also conducted. The significant independent variables were the same as those resulted from the forward method. For this reason, only results from the forward stepwise approach are presented here. SPSS software (version 16) was used to conduct the statistical analysis [30], [31]. The assumptions of linearity, such as homogeneity of variance, normality, and independence, have been investigated and satisfied.

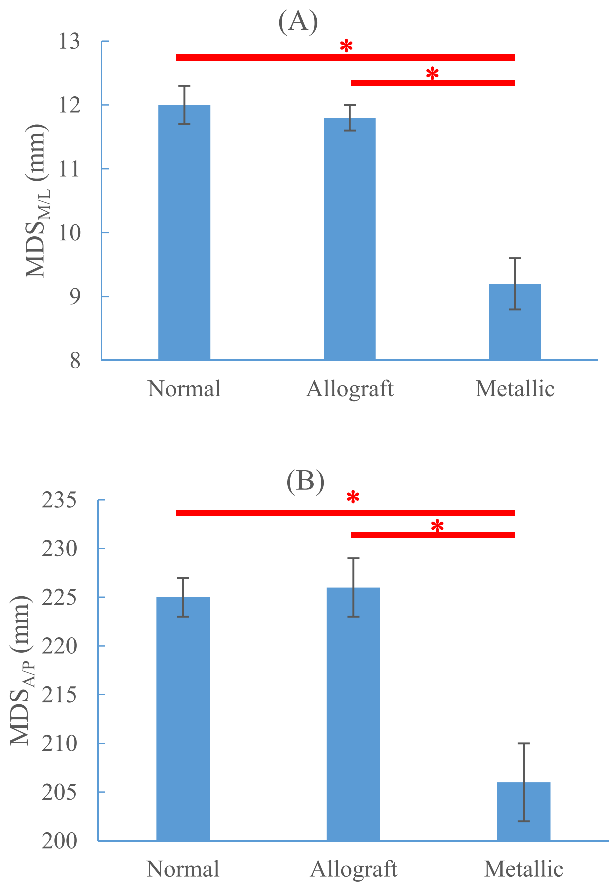

FIGURE 2. Margin of dynamic stability (MDS) for three groups with different types of knee replacements. Shown above are means with standard error range of the MDS in the (A) medio-lateral (M/L) and (B) anterior-posterior (A/P) directions. (*) indicates a significant difference.

III. RESULTS

A. $MDS_{M/L}$

The ANOVA revealed that there was a significant effect of knee replacement type on gait stability ($p < 0.0001$). Tukey's post-hoc tests showed that there was a significant difference between the $MDS_{M/L}$ of the metallic group (9.23 mm ± 1.51) compared to the $MDS_{M/L}$ of the normal (12.02 mm ± 1.19) and allograft groups (11.87 mm ± 1.22). Nevertheless, there was no significant difference between the allograft group and the normal group, as shown in Fig. 2 (A). Since there were significant differences between the groups in both directions, a regression analysis could be conducted.

B. $MDS_{A/P}$

The ANOVA revealed that there was a significant effect of knee replacement type on gait stability ($p < 0.0001$). Tukey's post-hoc analysis showed that there was a significant difference between the $MDS_{A/P}$ of the metallic group (205.79 mm ± 20.13) compared to the $MDS_{A/P}$ of the normal (224.91 mm ± 7.02) and allograft groups (226.28 mm ± 9.7). However, there was no significant difference between the allograft group and the normal group, as shown in Fig. 3 (B).

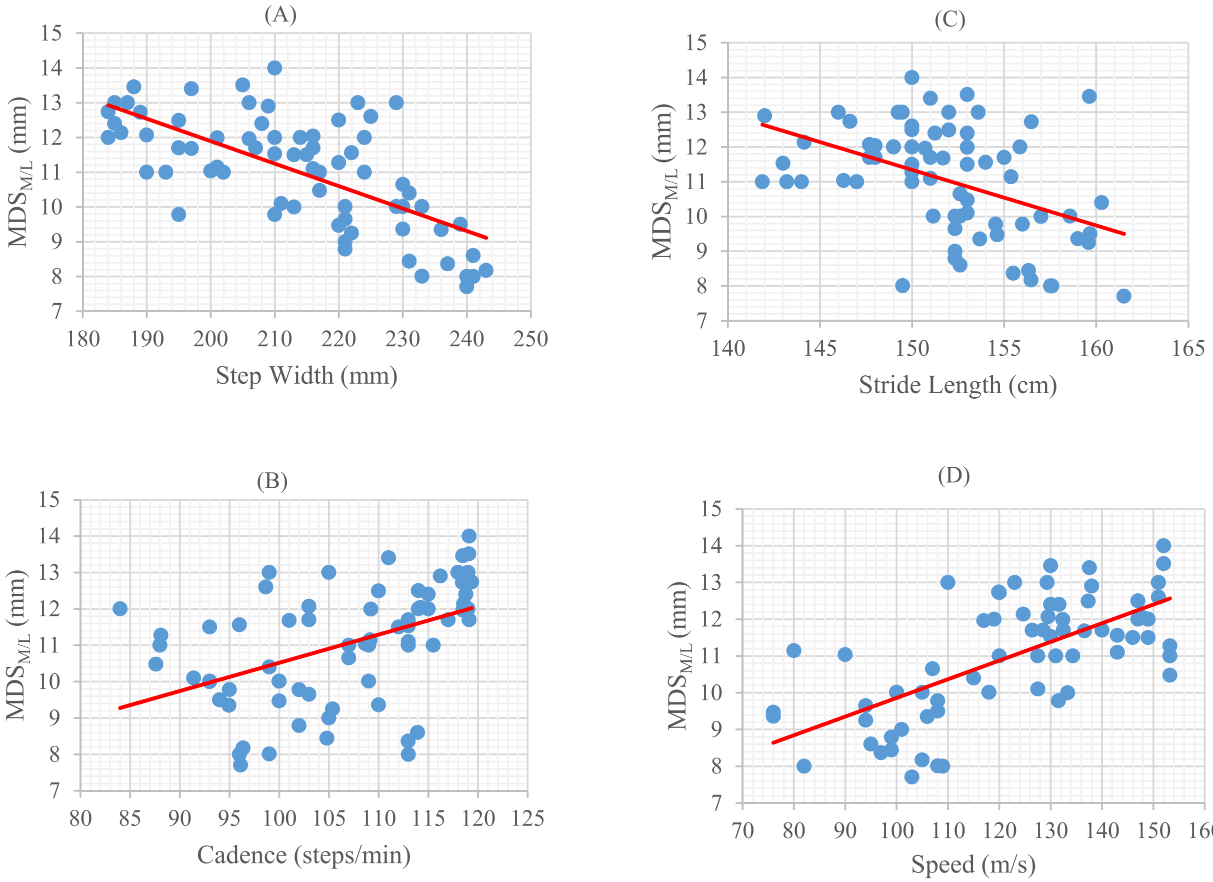

FIGURE 3. The relationship between margin of dynamic stability (MDS) in the medio-lateral (M/L) direction and (A) step width, (B) cadence, (C) stride length, and (D) walking speed.

TABLE 2. Coefficients, standard error, and significant values for margin of dynamic stability (MDS) in the medio-lateral (M/L) and anterior-posterior (A/P) directions.

Gait Parameters	$MDS_{M/L}$			$MDS_{A/P}$		
	β	Std. Error	p-value	β	Std. Error	p-value
Step Width	-0.37	0.006	< 0.001	-0.214	0.049	< 0.001
Speed	0.042	0.005	< 0.001	0.089	0.039	< 0.05
Cadence	0.05	0.01	< 0.001	0.313	0.08	< 0.001
Stride Length	0.004	0.08	0.21	-0.477	0.173	< 0.01

C. REGRESSION MODEL OF $MDS_{M/L}$

Table 2 shows the coefficients, standard error of the coefficients, and significant values for each independent variable in both regression models.

A stepwise multiple regression indicated that among all of the parameters, the only significant predictive factors of $MDS_{M/L}$ were step width, cadence, and walking speed ($p < 0.0001$). They accounted for 68%, 16%, and 4% of the total variance in $MDS_{M/L}$, respectively. Refer to "Equ. (3)" for the regression equation. As step width and stride length increase, the deviation of the XCoM from the lateral border of the BoS will shorten (i.e., producing better walking stability). Moreover, a faster cadence and walking speed result in decreased stability (i.e., the XCoM will be located further from the lateral border of the BoS). Figure 3 shows the relationship between the $MDS_{M/L}$ and (A) step width, (B) cadence, (C) stride length, and (D) walking speed.

$$MDS_{M/L} = 8.497 - 0.037 * StepWidth + 0.042 * Speed + 0.05 * Cadence \quad (3)$$

D. REGRESSION MODEL OF $MDS_{A/P}$

Step width, stride length, cadence, and speed were found to be significant predictive factors ($p < 0.0001$). They accounted for 64%, 11%, 5%, and 2% of the total variance, respectively (refer to "Equ. (4)" for the regression equation). As shown in "Equ. 4," an increase in step width and stride length brings the XCoM close to the front border of the BoS (i.e., producing better stability). On the other hand, an increase in walking speed and cadence deviates the XCoM further from the anterior border of the BoS. Figure 4 shows the relationship between the $MDS_{A/P}$ and (A) step width, (B) cadence, (C) stride length, and (D) walking speed.

$$MDS_{A/P} = 294.92 - 0.241 * StepWidth - 0.477 * Stride\ Length + 0.313 * Cadence + 0.089 * Speed \quad (4)$$

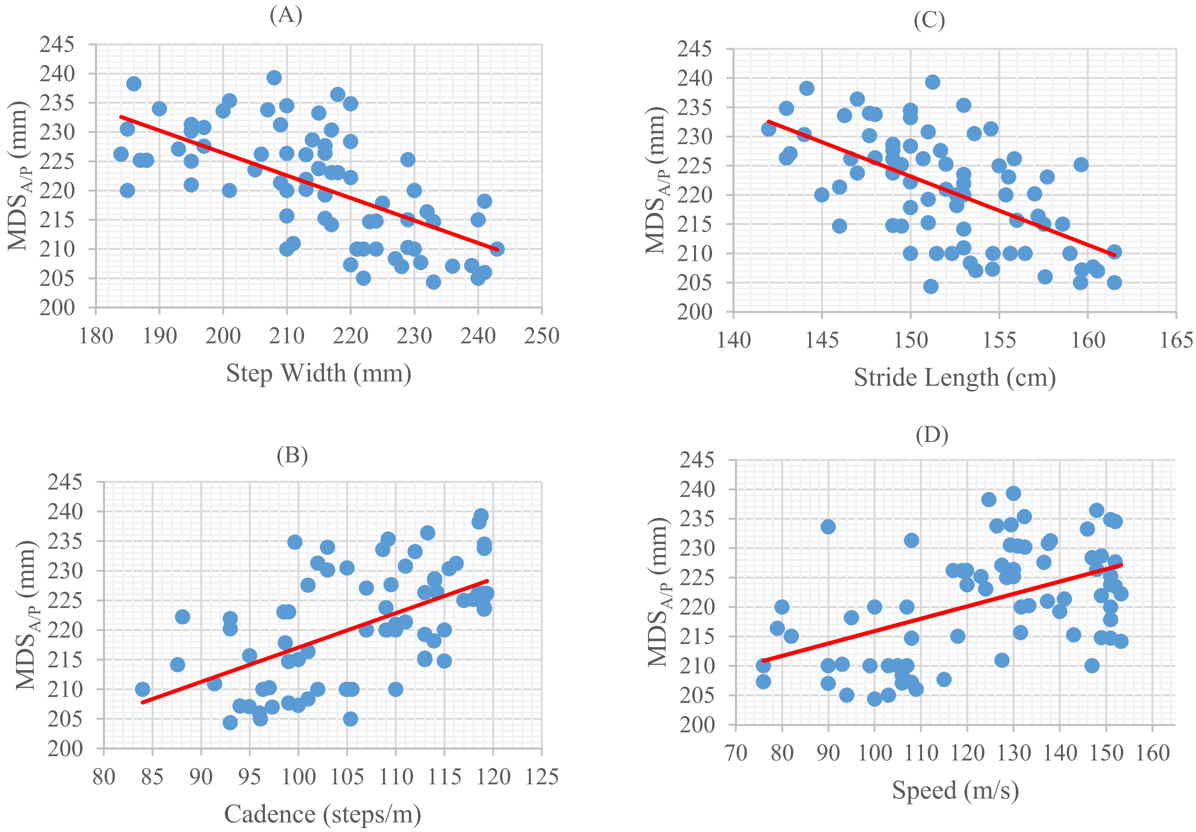

FIGURE 4. The relationship between margin of dynamic stability (MDS) in the anterior-posterior (A/P) direction and (A) step width, (B) cadence, (C) stride length, and (D) walking speed.

E. VALIDIATION OF THE REGRESSION MODELS

One of the most important steps in developing a regression model is the testing of its validity. The validation process involves testing the goodness of fit of the regression. Examples of measures of goodness of fit are 1) the coefficient of determination (R^2, which indicates the percentage of the variance explained by the independent variables in the regression model), 2) standard error of the estimate (S, which indicates how the data is distributed around the regression line), and 3) root-mean-square error (RMSE, which measures error in the prediction of quantitative data). Table 3 shows the values of R^2, S, and RMSE for both of the models that were developed. Large R^2 values indicate that a large percentage of the variance in the model was explained by the independent variables. Small values of S indicate that data are scattered close to the regression line. Likewise, small RMSE values indicate that the differences between the predicted and actual values are small.

It is worth noting that in the $MDS_{A/P}$ model, the values of S and RMSE were higher because the standard deviation (SD) of stride length (in which motion was measured in the forward direction, i.e., the A/P direction) was 0.048 m, which was larger than the SD of step width (SD = 0.015 m, in which motion was measured in the sideways direction, i.e., the M/L direction). Moreover, the SD of walking speed—which was measured in the same direction as the stride length—was also large (SD = 22.12 m/s). In calculating the XCoM, a higher walking speed adds more value to the CoM, which results in a further addition to the XCoM from the BoS.

TABLE 3. Measures of goodness of fit for both models (MDS: Margin of dynamic stability, M/L: Medio-lateral, A/P: Anterior-posterior).

Goodness of fit measures	$MDS_{M/L}$	$MDS_{A/P}$
R^2	88%	81%
S	0.7746	5.7
RMSE	0.7468	5.511

IV. DISCUSSION

Compared with multi-legged animals, those who walk on two legs have more difficulty maintaining their balance since they have smaller BoS area [32], [33]. Control of locomotive stability is considered a complicated task since it needs the coordination of nervous, sensory, and motor systems to control the CoM in an accurate manner. The objective of this study was to develop regression models that predict A/P and M/L gait stability based on gait parameters such as walking speed, cadence, step width, and stride length. In previous studies involving the development of stability regression models, subjects were asked to alter and change their walking patterns in order to create different gait parameters [11]–[15]. Such a method has the potential to introduce experimental error, since subjects are not walking with a comfortable and regular walking pattern. To prevent such an error and to ensure that participants would walk with their natural gait, the sample chosen for this study included patients who had atypical walking patterns [18]. Patients who participated in this study had undergone knee replacements with either allograft or metallic replacements. Step width and stride length explained the highest percentage of the total variance in both models. An increase in step width and stride length resulted in better walking stability in both directions (i.e., in the A/P and M/L directions). These results are in agreement with previous studies that concluded that widening the area of the BoS is one strategy to improve walking stability [34]–[36]. A large BoS area causes the XCoM to be brought closer to the center of the BoS, which is the optimal position for stability [37]. An increase in walking cadence and speed resulted in further deviation of the XCoM from the BoS in both directions (i.e., decreased gait stability). This result confirms the findings of previous studies which concluded that a higher cadence was a sign of perturbed gait [21], [22], [29], [38], [39]. A higher cadence forces the body to shift weight rapidly to the other leg during walking. This rapid shift significantly affects the kinematics of the trunk, exposing the location of the XCoM to sudden and further movements [40]. When calculating the position of the XCoM, if walking speed increases, the value that will be added to the CoM will also increase. This increment results in an XCoM that is further from the body (which in turn is further from the BoS). This result is in line with previous studies that found that subjects tend to walk with a slower gait in order to improve stability [41]–[46]. Several limitations of the study design could be addressed in future research. First, the sample size was not large. It was difficult to find patients who had undergone a replacement of a knee joint. Second, participants walked on the walkway barefoot, in order to ensure a correct and accurate reading of the BoS area. As such, the role of shoe friction could play an important role in improving balance. Moreover, future studies should investigate other factors, such as gender, weight, height, and age that might have significant effects on walking patterns. Moreover, the contribution of muscular activity, and mental capabilities during walking should be taken into consideration in analyzing gait stability. Additionally, the effect of manual material handling (MMH) activities should be investigated using regression models to measure the relationship between the variation of the load being carried and walking stability. This will provide guidance to the optimal weight that will not perturb gait stability. In conclusion, as a strategy to improve walking stability, fallers and fall-prone people should walk with an adequate BoS area, and with a lower cadence and speed to prevent falling. The models developed in this study will help in predicting and measuring A/P and M/L walking stability based on spatio-temporal gait parameters and without the use of advanced equipment and tools. Moreover, the results obtained in this study contribute to an understanding of the role of gait patterns in walking stability and to how gait strategies might be taught in physical therapy programs to minimize the risk of falls.

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