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Determination of most important predictor of Vertical Ground Reaction Force (VGRF) and threshold value of fracture among young adults

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Abstract: *Background:* Lower-limb stress fracture is one of the most common type of injuries among soldiers worldwide. Understanding the kinetics and physiological responses of military footwear has immense importance increasing mobility, performance/combat readiness and decreasing risk of footwear related injuries. *Objectives:* In the present study key factor of fractures and limiting value of fractures wearing combat boots of different weight [heavy weight (HW) and light weight (LW)] was investigated using bioinformatics approaches. *Method:* Twenty (n=20) Indian Infantry Soldiers with mean ± SD age, height and weight of 35 (±6.0)years, 181.3(±5.1)cm, 82.5 (±5.2) kg, respectively, volunteered for the study. This study has used Artificial Neural Network (ANN) for entropy measurement to predict the relationship of input variables of stance phase of gait cycle (Heel strike, toe off, heel strike to toe off duration, braking force, propulsive force, appearance time of braking force and propulsive force) with the output variables [Coefficient of friction (CoF) & impulse]. *Results:* Based on the outcomes it appears a better and authentic explanation to consider duration of heel strike to toe off value of a complete gait cycle to evaluate Impulse as a measure of fractural injuries. Likewise appearance time of braking force can be used to evaluate Coefficient of frictional movements as a measure of fall and risk injuries. *Conclusion:* Limiting value of VGRF for fracture was found to be 792N. Risks of metatarsal fractures were found to be higher in HW boots as the VGRF value is closer to fracture value at same walking speed.

Keywords: ANN, Data mining, Fracture, Footwear, Injuries, VGRF.

Introduction

Lower-limb stress fracture is one of the most common types of injuries among soldiers worldwide [1-3]. There have been quite a lot of studies focusing on the association between stress fractures and biomechanical factors. Stress fractures are considered overuse injuries associated with the mechanical fatigue of bone. Long period of repetitive loading, such as that incurred during running leads to the formation of bone micro damage [4]. If the rate of this damage exceeds its tolerance level, it may propagate to a critical length [5]. For the physiological loads related to human locomotion, a 10% reduction in strain magnitude can correspond to a 100% increase in the number of cycles to failure [6].

Multiple studies have reported that metatarsal loading caused either by the footwear itself or the changes to running biomechanics associated with the footwear [7]. In the current study, the ground reaction force and loading rate are examined. There is disagreement in the literature about whether the history of stress fractures is associated with ground reaction forces (either higher or lower than control), or with loading rates. Globally reported studies on military footwear, biomechanics and physiological responses in simulated as well as field conditions are less reported. No reported study is available in India on military footwear in respect to biomechanical and bioinformatics responses.

As per the geographical diversity, soldiers are posted in adverse environmental conditions high altitudes, desert and jungle environments. At the same time, occupational tasks by military personnel are also often carried out in various terrains, ranging from flat even surfaces, or inclined uneven. Understanding the kinetics and physiological responses of military footwear has immense importance increasing mobility, performance/combat readiness and decreasing risk of footwear related injuries. Thus there is a need to identify the major key variable of fractures, fall and risk injuries during level walking as GRF, moment and co-efficient of friction are very important in gait analysis to study the kinetic interaction with the ground and to estimate the joint kinetics and predicting injury risk [8].

Co-efficient of friction plays vital role to predict the fall and risk injuries. Various parameters of measured GRF during human dynamic motion have been used as the main factors in the analysis of gait [9-10], sports [11], rehabilitation [12] and disease [13]. Injuries often occur while performing high impact landing movements. During landing, vertical GRF is typically much greater than GRFs in the antero-posterior direction. So, it has been already studied in greater detail [14] but there are some controversies which component of GRF has extensive impact on fractural and fall injury risk prediction. Therefore, we have used a new bio-informatics approach to the present work to find out first the key factor of fractures and limiting value of fractures wearing combat boots of different weight by data mining.

Artificial neural network (ANN), a typical data mining method, is widely used in mapping and simulating the relationship between a set of input and output variables [15]. ANN is usefully applied to various areas such as chemistry, mechanics and physics [16] particularly for the prediction of ground reaction force, joint moment, and muscle force in the area of biomechanics [10]. Based on such advantages, this study introduces the artificial neural network method to overcome the limitation to predict injury risk from any of the GRF parameters which strongly influence the impulse of movement and co-efficient of friction from the values one cycle of gait in our existing studies.

In detail, we applied a data learning based artificial neural network model to find out the undefined factor which can predict chances of injury risk related fractures and fall injuries that can be occurred during normal gait. In addition, as a result of this study, we compared the results of two different foot (left and right) and different types of footwear (HW & LW).

Material and Methods

Subject details: Twenty (n=20) Indian Infantry Soldiers with mean ± SD age, height and weight of 35 (±6.0)years, 181.3 (±5.1) cm, 82.5 (±5.2) kg, respectively, volunteered for the study. The volunteers had no history of lower limb problems or surgery. Total (20 subjects x 10 trials) = 200 trials have been carried out.

Subject preparation: Half of the participants have been allowed to wear HW boots first and then LW boots for the experiment to carry on as in the protocol mentioned further. On the other hand, other half have been allowed to wear LW first and then HW to nullify all the possibilities of biasness during experimentation. It is called 'balance order experiment'. Accordingly, they prepared for participation.

Experiment details: In this study, it is proposed to investigate that the effects of HW and LW from the kinetic point of view whether LW boot is beneficial in compare to the HW boot at the time of level walking. Accordingly Pilot experimental trials have been carried out on each subject while walking on the force plates at comfortable normal pace, familiarizing with the laboratory condition, experimental design and collection of kinetic data.

Two piezoelectric sensor based force platforms (Model 9286AA, Kistler Instrumente AG, Winterthur, Switzerland) were installed by pit installation method at the center of the 10 m walkway and area of 3 m x 1.5 m area at the center within the walkway where the force plates were placed [17]. The weight of the individual were recorded prior to collection of data on 2 different force plates to neutralize the output by individual's

weight. 2 force plates were used during walking trials, weight neutralization were done on 2 force plates. Bioware software (Version 3.24; kistler Instrumente AG, Winterthur, Switzerland) was used to collect and process data. The data acquisition frequency was 200 Hz [17-18].

Data collection: For each participant, data were recorded for 4 seconds while walking each of the experimental condition on the force plates. Data from heel contact to toe off (Contact phase) of each foot were included for analysis and subjected to statistical treatment. For each participant, 5 trials were recorded for each condition. As per the combination matrix (5 trials x 2 Boots), a total of 10 experiments for each volunteer were performed. 3 successful trials were selected for further processing and analysis in each condition for each subject. These trials were considered as successful where a comfortable walking speed range and natural gait pattern of individual has been maintained.

Application of bioinformatics principles on above data: The output has been used to understand whether any threshold value of injury prediction could be used in combination with biomechanical gait analysis for screening individuals who are at risk of developing early joint injury. This may reduce the incidents of fall injury, thus improving quality of life and occupational health of the individual. The present study endeavored to predict the impulse and co-efficient of friction excreted on the feet during Gait analysis by ANN. The data for the gait analysis were obtained by Kistler's Force Plate System. In order to predict the accuracy of the measurements, Artificial Neural Network (ANN) has been used to analyze in swing and stance phase.

- *Search strategy:* Some computerized searches were performed to compile peer reviewed journals, conference articles and some review articles. Seven key databases were systematically searched for identifying relevant studies. These databases included: Scopus, PubMed, Science Direct, Medline. Journal searches focused on those journals that were most likely to publish foot related problems, injuries, fractures and measuring the GRF parameters in different way. Relevant articles were identified by cross referencing the citation lists of the articles sourced from the electronic search.
- *Redundancy elimination:* Redundant articles were eliminated to remove duplicates.
- *Selection of studies:* Identified articles or abstracts were ranked with statistical significance by Medline ranking. Finding out the limiting value of injury at different walking speed from data mining.
- *Validation of experimental data*: Experimental data has been taken from effect of light weight shoes on kinetic parameters during level walking and risk of injuries have to be assessed in LW and HW shoes by prediction equation using the data from meta-analysis.

Results

Artificial Neural Network Structure:

Items	Details
Subjects	Healthy subjects: 20 male
Training Data	Randomly selected 14 subjects among the total of 20 subjects. One gait cycle of data, 100% normalized, of the randomly selected 14 subjects x 10 input variables (10x1400)
Validation Data	The dataset of remaining 6 people who were not selected as part of the training group
Validation method	10-fold cross-validation
Input	One gait cycle of data, 100% normalized, of the 6 people who were not used in model learning x 10 input variables (10x600)
Output	Impulse and Coefficient of friction output
ANN structure (1-1-1)	1 input layer: 10 nodes (secured independency) 1 hidden layer: 3 nodes (decide by substituting at 1~2n+1 one by one, following the Kolmogorov theorem) 1 output layer: COEFFICIENT OF FRICTION & IMPULSE in different model

Input Variables: HS- Ground reaction force at the time of striking heel, TH- Ground reaction force at the time of ending heel strike of one foot and starting toe off of another foot, TO- Ground reaction force at the time of toe off, AOH- Appearance time of Heel strike force in a proper gait cycle, AOT- Appearance time of Toe off force in a proper gait cycle, HSTO- Duration of one gait cycle i.e. Heel strike to toe off, PF- Propulsive force, BF- Braking force, APF- Appearance time of propulsive force in a proper gait cycle, ABF- Appearance time of braking force in a proper gait cycle.

Output Variables: IMPULSE- impulse is approximated by body weight multiplied by the amount of time the foot is in contact with the ground which indicates the heel and metatarsal injury risk; COF (Co-efficient of friction)- Co-efficient of friction is predictor of fall and risk injuries.

Prediction of Most Important Variable Affecting Impulse And Coefficient Of Friction: The measured kinematics during level walking were similar to general patterns observed in previous studies [19]. To present the accuracy of impulse and coefficient of friction of force prediction model objectively, the prediction results were divided into variable affecting impulse and coefficient of friction so that we can identify the most important predictor for fractural injury and fall-risk injury consecutively. Similar methods and variables were applied for both the prediction model and the data we have taken were the data of entire gait cycle.

Identification Based on Entropy: To identify the important variables of a system subjected to many random variables above mentioned, a novel entropy-based importance measure for random variables is proposed in this paper. According to the information theory [20-22], entropy is a measure of uncertainty that is associated with a random variable. The method evaluates the effect of a random variable on the output responses by calculating the change of the entropy value. This technique focuses on the influence of input uncertainty on the entropy of the output responses and can be easily extended to the case taking the correlations among the random variables into consideration. This result verifies that a parameter, which has a major effect on the variance or the Kullback–Liebler divergence, mutual entropy, and the distribution of the output is not necessarily the parameter that has a major influence on the entropy of the output [20-22]. From figure 1 it was observed that the entropy is highest in appearance time of Braking force (ABF) while measuring the most important predictor of fall risk injury i.e. Coefficient of friction (COF) and similarly from figure 2 it was observed that the entropy is highest in Heel strike to Toe off time (HSTO) while measuring the most important predictor for fractural injury i.e. Impulse.

Fig-1: In case of left& right foot using HW and LW, *Appearance time of Braking force* (ABF) is the most important variable to predict Coefficient of friction as the entropy is higher (-0.10) than the others after plotting ANN

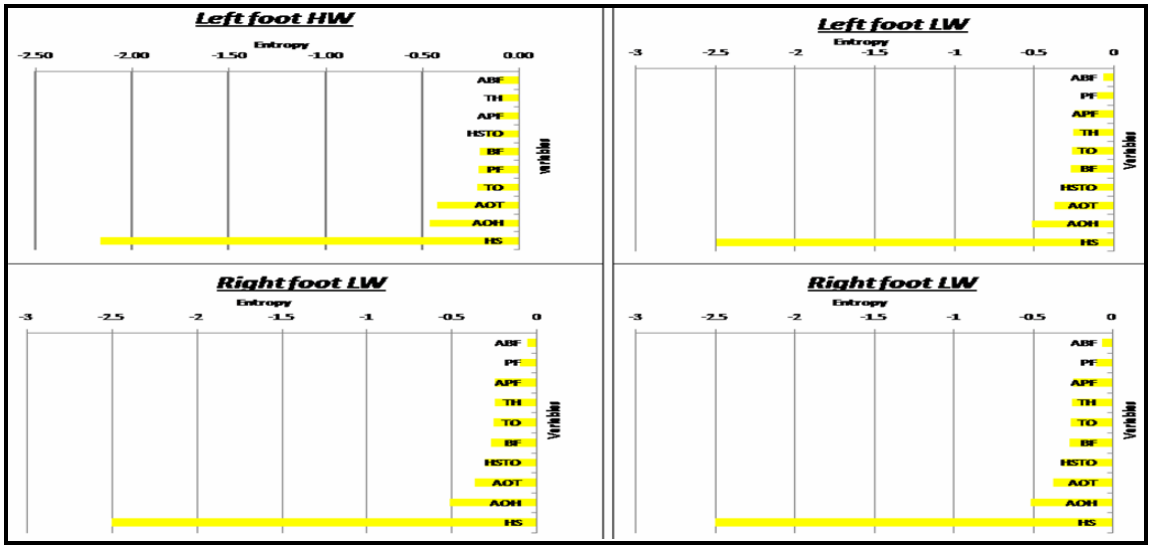


Fig-2: In case of left & right foot using HW and LW, *Heel strike to Toe off* (HSTO) is the most important variable to predict Impulse as the entropy is higher (-0.05) than the others after plotting ANN

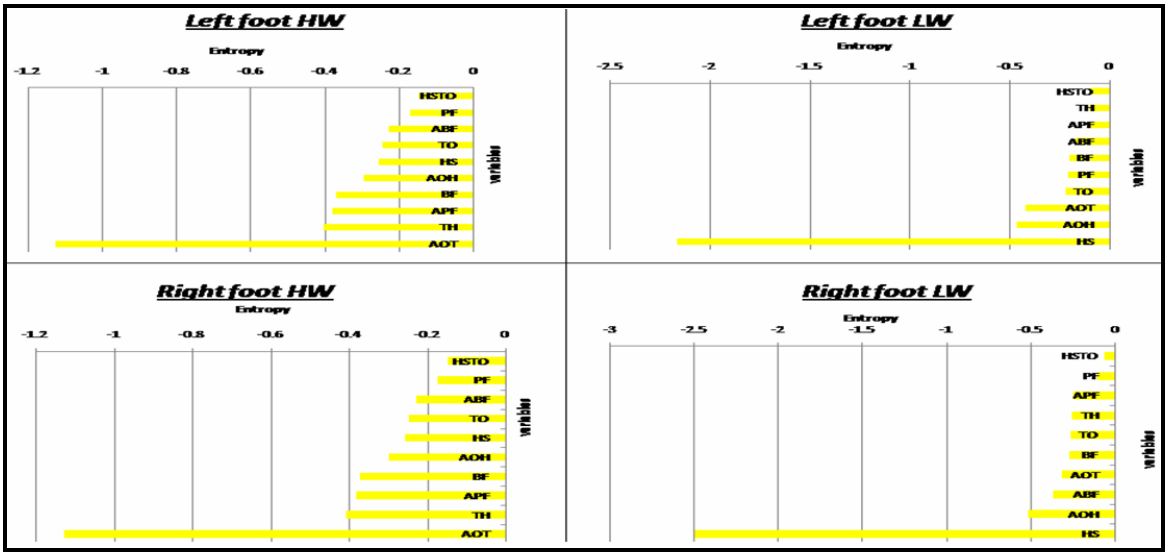


Fig-3: ANN architecture selected as prediction model of Coefficient of friction (COF) in right foot using HW & LW boots (Same result in left foot also)

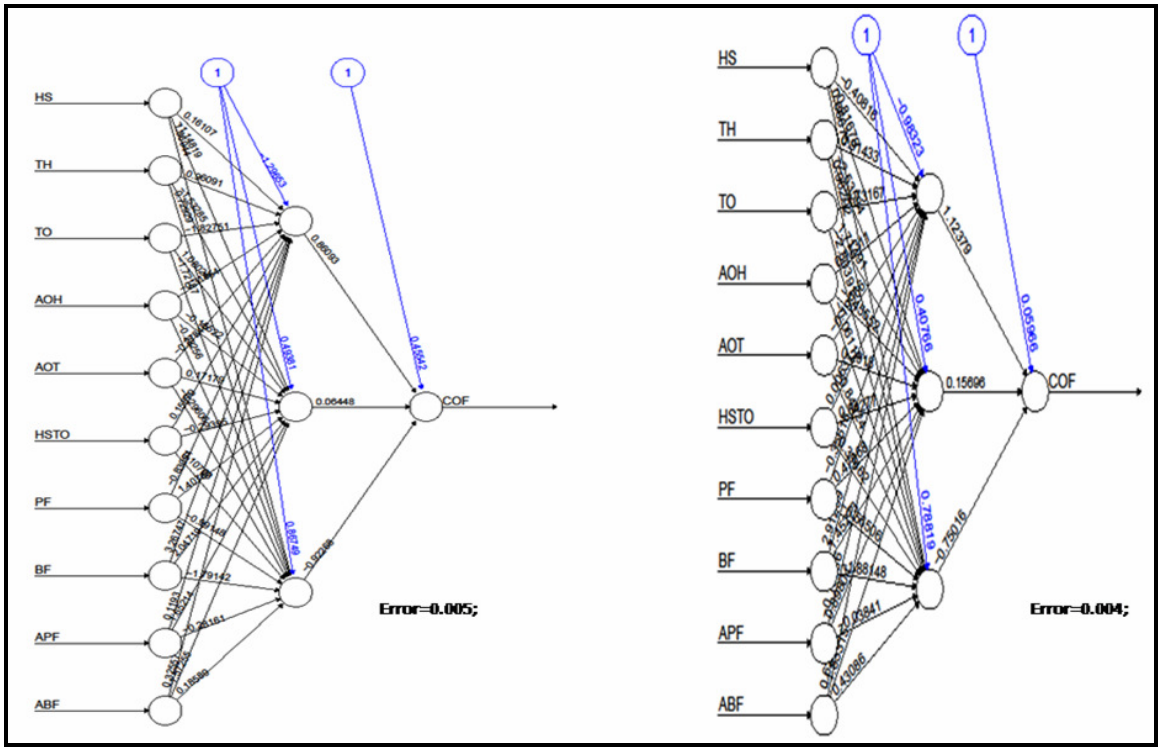
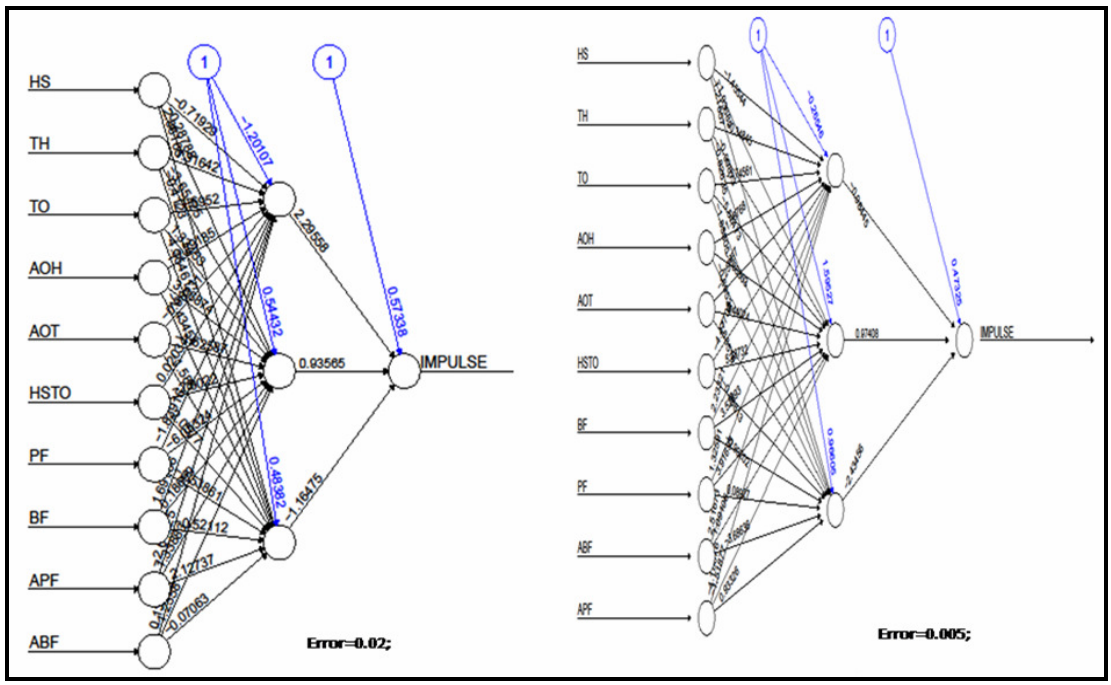


Fig-4: ANN architecture selected as prediction model of IMPULSE in right foot using HW & LW boots (Same result in left foot also)



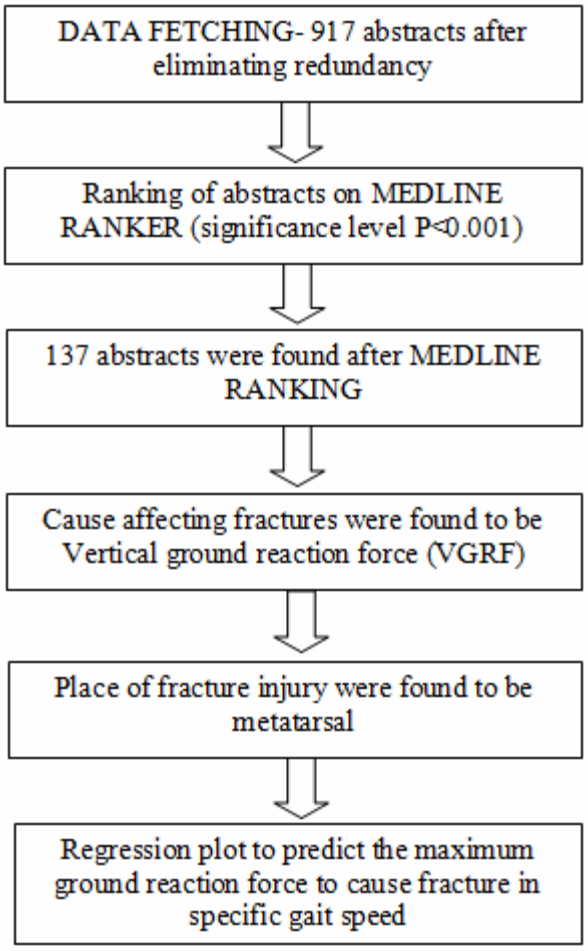
Variables of interest and query design based on data fetching from PubMed and Science-direct;

- *Search strategy:* A computerized search was performed to compile peer-reviewed journals, conference articles and theses in English. Nine key databases were systematically searched for identifying relevant studies till 2019. These databases included: Scopus, PubMed, Medline. Each database was searched using the following search terms (refer table 1). Journal searches focused on those journals that were most likely to publish research related to foot injury protection. Relevant articles were identified by cross referencing the citation lists of the articles sourced from the electronic search.

Table-1: Combination of Query design and variables of interest

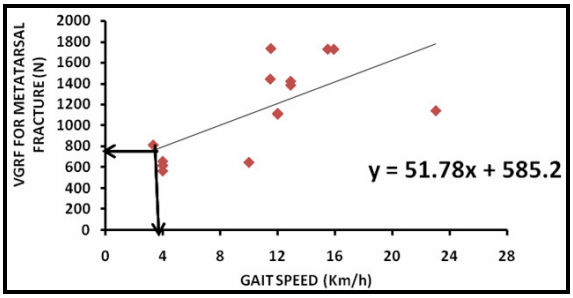
Variables of Interest	Query Design	No of Unique Articles in PubMed
Foot	(((((Foot) AND injury) AND force) AND pain) AND fractures) NOT diabetic	337
VGRF	(((vertical) AND ground) AND force) NOT sports	146
Antero-posterior Force	((((braking) AND propulsive) AND anteroposterior) AND injury) NOT sports	88
Impulse	((((VGRF) AND foot) AND injury)AND impulse) NOT sports	56
Fracture	(((VGRF) AND impulse) AND metatarsal)AND fracture)AND lower limb) NOT sports	57
injury	((((Impulse) AND VGRF) AND fracture) AND injury) NOT sports	153
metatarsal	((((lower limb) AND foot) AND metatarsal) AND injury) NOT sports	207
Total Articles **Unique article after redundancy elimination**		**1044** **917**

- *Data extraction for plotting regression equation to predict the VGRF causing fracture*



Identification of maximum VGRF: It was found from regression model of injury prediction in metatarsal, Vertical ground reaction force (VGRF) depends upon gait speed. Prediction equation of assessing VGRF for fracture is: y= 51.78x+585.2 [y= VGRF for fractures, x= gait speed] From our methodology of level walking on force platform , gait speed was approximately 4km/h, so predicted VGRF for metatarsal fracture was 792 N. We have also found from this current methodology that in 4 km/h walking speed, average VGRF wearing HW is 730 N and LW is 698N. VGRF found to be most important factor to cause metatarsal fractures at level walking. Limiting value of VGRF for fracture was found to be 792N using the value of (plotting a regression curve) data mining from available literatures. Risks of metatarsal fractures are found to be higher in HW boots as the VGRF value is closer to fracture value at same walking speed.

Fig-5: Regression plot of maximum VGRF for metatarsal fractures in specific gait speed from data mining from available literatures



Discussion

Results of this study suggested that in case of both feet and both shoes (HW & LW), appearance time of Braking force (ABF) is the most important variable to predict Coefficient of friction as the entropy is higher than the other gait parameters after plotting ANN. So, it can be interpreted that fall injury risk is dependent upon by the time braking force has been appeared in one cycle of gait. Similarly, Impulse is another predictor of fractural injury in kinetic study. Heel strike to Toe off duration (HSTO) in gait cycle is the most important variable to predict Impulse which in turn can assess the chances of fractural injury.

For the first time among Indian military population, ANN and data mining together were able to map the underlying data structure related to predict injury risk from any of the GRF parameters which strongly influence the impulse of movement and co-efficient of friction from the values one cycle of gait in existing studies. In detail, the regression models from data mining were able to find out the limiting values for fractural injury and which boots have greater risk of fracture. The knowledge of the important region of an input variable can provide valuable information to characterize, understand, and improve a model through additional modeling or testing [23].

In this study, all the mentioned input variables are phases of entire gait cycle which are having unknown effects on impulse and coefficient of friction. After the important regions of the random variables have been identified, the resources, such as experimental designs, can focus on the important regions

that affect the system output response the most. It is, therefore, significant to evaluate the effect of the random variable within a given range of interest. Based on the entropy of the random variable, the effect of the random variable within any domain of interest on the output response can be described by the presented global sensitivity indicator.

Until now, previous studies related to GRF prediction were limited to static postures and gait. Audu et al. [24-25] estimated GRF in a static posture using the optimization techniques, and the errors between measured and predicted In previous studies related gait cycle and ANN, comparison described between the predicted and measured value [26-27] of single and double support phase of gait cycle to solve problems of an indeterminate system that occurs in double support phase.

The results of those studies are expected to be used as raw GRF in future motion analysis as well as input data of inverse dynamics analysis that calculate joints dynamic information. But this study adopted some new angle of ANN in terms of entropy measurement to predict the importance of input variables of stance phase of gait cycle on the output variable. The results allow the judgment that, human movement has same effects on both the feet and both the boots as from entropy measurement it was found vertical GRF impulse was mainly affected by the duration of heel strike to toe off and CoF was mainly affected by the appearance time of braking force in every condition.

Now, the results of another part of this study suggested the assessment of fractural injury risk in HW & LW. To evaluate the risk of injury, force plates are commonly used in kinematic laboratories to provide GRF measurements for amplitude, direction, and time. These parameters are readily available and are relatively easy to analyze, but the correlation between them and the related risk of injury isn't well understood [28-30]. There is an unknown window of assessment of fractural injury by VGRF values among Indian Army population. Nigg [29] concluded that the GRF levels during running are typically within an acceptable range for cartilage, bones, ligaments, and tendons. However, during high-velocity landing, GRFs may be greatly increased, which can lead to ankle sprain and other injuries. So, further study is required to understand how the boots affect the risk of injury.

There are many types of injuries, but they are generally classified into two main categories: Fractural and non-fractural. A systematic review concluded that no one was more superior to the other, and both could effectively assess the incidence of ankle sprains among injured individuals that how much VGRF is responsible for fracture in real-time scenario. When comparing the influence of boots on the VGRF, it is necessary to consider the boots related injuries also.

Therefore, this current meta-analysis pooled all types of threshold values of VGRF responsible for fractural injuries together to find out the limiting value of VGRF at different speed for studying their effects on two types of boots. But only Brizuela et al. [31] studied the influence of top height on GRF performances during level landing. To avoid bias, this type of article was not considered in this meta-analysis.

Meta analysis leads to plot a regression model considering all VGRF values at different walking speeds and the limiting value of fracture was found to be 792N at 4kmph walking speed. While this value was compared with real time value of VGRF under same above mentioned experimental protocol, valuable information has been introduced that HW (730N) having greater risk of fractural injuries than LW (698N) as the value is more closer to the limiting value found in meta-analysis (figure 5).

Based on these results, it appears a better and authentic explanation to consider duration of heel strike to toe off value of a complete gait cycle to evaluate Impulse as a measure of fractural injuries and appearance time of braking force to evaluate Coefficient of frictional movements as a measure of fall and risk injuries. After that threshold VGRF for Indian army population has also been determined at normal walking speed (4kmph) and LW boots provide more safety than HW boots which indicates that military footwear

has immense importance increasing mobility, performance/combat readiness and decreasing risk of footwear related injuries.

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