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Methods to quantify gait rehabilitation following lower limb fractures

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ABSTRACT

Lower limb fragility fractures require long-term rehabilitation and are also very expensive to treat. Clinically, early weight bearing and walking stability were reported as key measures of fracture restoration. This study introduces methods to numerically quantify these performance indices for a range of ankle and knee joint fractures. As a follow-up of initial treatment, experimental data was collected using force plates from 367 subjects divided into seven groups: ankle fracture (AF), lower leg ankle fracture (AL), calcaneus foot fracture (CF), knee tibia fracture (KF), knee patella fracture (KP), kneecap rupture (KR), and normal limb (NL). For each joint, data was analysed to evaluate intralimb and interlimb weight-bearing and walking stability for all fracture conditions. These thresholds were statistically compared with normal subjects. Some advantages of evaluating fracture restoration indices over the others include:

- to quantify fracture restoration (weight-bearing, walking stability, and gait symmetry) using minimum setup and signal requirements.
- to provide comprehensive tools to assess and overcome fracture-associated complications through a detailed preview of fractured limb functionality during subphases of a gait cycle.
- in clinical research, such assessments are important as a reference to evaluate existing or new rehabilitative interventions.

Specifications table

Subject Area:	Medicine and Dentistry
More specific subject area:	Physical Therapy, Movement Analysis
Method name:	Fracture Rehabilitation through Gait Assessment
Name and reference of original method:	Name: fracture restoration evaluation Reference: Prior methods evaluated fracture restoration indices using different biomechanical signals and measurement systems: 1. Weight-bearing (Pfeufer et al., Injury. 2019:50:1324-8 [2]) 2. Walking Stability (trunk acceleration method – Vieira et al., J of Biomechanics. 2017:54:73-79 [9]) 3. Gait Symmetry (Mahmood et al., Med Eng Phys. 2021:100: 103720 [14]) This study optimises existing fracture restoration evaluations by evaluating the above three performance indices using minimum biomechanical signals and associated hardware requirements.

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Resource availability:	All supporting data accessible through the Elsevier repository as: 1. Ankle Fractures https://data.mendeley.com/datasets/zh5zjr44zk/1 2. Knee Fractures https://data.mendeley.com/datasets/8584gn4y37/1

Background

Early weight-bearing, walking stability and gait symmetry have been reported as key performance indices to evaluate gait restoration following lower limb fractures [1-3]. Recent studies reported that modern rehabilitation centres used instrumented gait data to diagnose, plan, and evaluate rehabilitation outcomes [4,5]. Gait data such as spatiotemporal parameters were used to evaluate interlimb gait symmetries [3,6] however, they provide little information about walking stability and weight-bearing ability. Alternatively, ground reaction forces (GRF) have been reported as a measure of weight-bearing ability and walking stability [1,7-9] however, the thresholds of GRF(s) over the entire gait cycle as reported earlier provide little information about gait variability and symmetries during subphases of a gait cycle. Thus, the breakdown analyses of gait into subphases can provide detailed insights into fracture healing and hence reduce the risk of overloading during the rehabilitation period. This study presents methods to evaluate weight bearing, walking stability, and gait symmetry as fracture restoration indices using: 1) minimalistic signals (GRF) and hardware requirements, and 2) extracting maximum information by analysing data for gait inner phases. These methods optimise the existing instrumented techniques used for rehabilitation evaluations in response to clinical interventions.

Methods detail

Fracture restoration measurement tools

Ground reaction forces (GRF) are reported as a standard tool used clinically to measure human locomotion and to diagnose and evaluate patients' gait performance [5]. A gait cycle can be described using GRF waveforms as shown in Fig. 1. During a normal gait, weight acceptance by either of the limbs takes place in three subphases: 1) first double limb support (first 30% of stance); 2) single limb support (31-70% of stance); 3) second double limb support (71-100% of stance) [10,11]. During the first double-limb support period, the fractured limb accepts body weight gradually named as the loading phase while the intact limb undergoes the unloading phase. During single-limb support, the affected limb accepts the whole-body weight independently without the support of the intact limb. Lastly, during the second double limb support period, the affected limb pushes the ground backwards to get a forward lift named the unloading phase while the intact limb undergoes the loading phase. In this study, the vertical component of GRF (V-GRF) is used to quantify the weight-bearing ability of the fractured limb while the anterior-posterior and medial-lateral GRF components (AP-GRF, ML-GRF) are used to quantify neuromuscular control towards walking stability.

Another important aspect to quantify fracture restoration is the dependency of the affected limb on the intact side (gait symmetry) which was speculated to be increased significantly with lower limb injuries [4,12]. During the first double limb support, the affected limb executes weight acceptance (loading phase) and the intact limb executes weight unloading and vice versa occurs during the second double limb support phase [13,14]. Such interaction between opposite limbs provides vital information on interlimb gait symmetry as a measure of fracture restorations [4]. In the current study, gait symmetry is also evaluated in terms of interlimb correlations during both the first and second double limb support phases.

In general, walking stability refers to the ability of humans to maintain/regain body movements without falls [15]. Prior review studies [16,17] categorised gait dynamic stability assessments mainly into the margin of stability, the Lyapunov exponent, the Fluquent exponent, the variability measure and long-range correlations. In this study, variability measures and correlation methods are applied. The variability in CoM-acceleration (or trunk acceleration) both in anterior-posterior and medial-lateral directions is used to quantify gait stability. Also, the interlimb correlation method is applied to measure gait symmetry. The data from healthy subjects acts as a baseline in almost all gait assessments. In this study, an increase/decrease in the variability of CoM-acceleration, computed for impaired subjects, gives the measure of poor walking stability compared with normal subjects [18]. The statistical analysis reveals whether this difference is significant or not.

Experimental data collection

A dataset collected from fracture healing patients and maintained by the Austrian Rehabilitation Centre [5] was analysed in this study. Experimental data was collected from patients who underwent surgeries after fractures and currently experiencing administrative therapies. The data consisted of three-dimensional ground reaction force (3D-GRF) and two-dimensional centre of pressure (2D-CoP) signals recorded from 2084 fracture patients and 210 healthy individuals. All subjects were instructed to walk at their preferred pace and trails were recorded at 2kHz using two force platforms installed on a 10-meter-long walking track. In this study, data recorded for a range of ankle and knee fractures was analysed. Data from healthy subjects act as a reference for statistical analysis. The criteria followed to sort ankle and knee patients from the metadata file include patients who just started therapy, walked at a preferred speed, trial recorded by wearing shoes, data collected from mixed genders, and data logged from both left and right limbs.

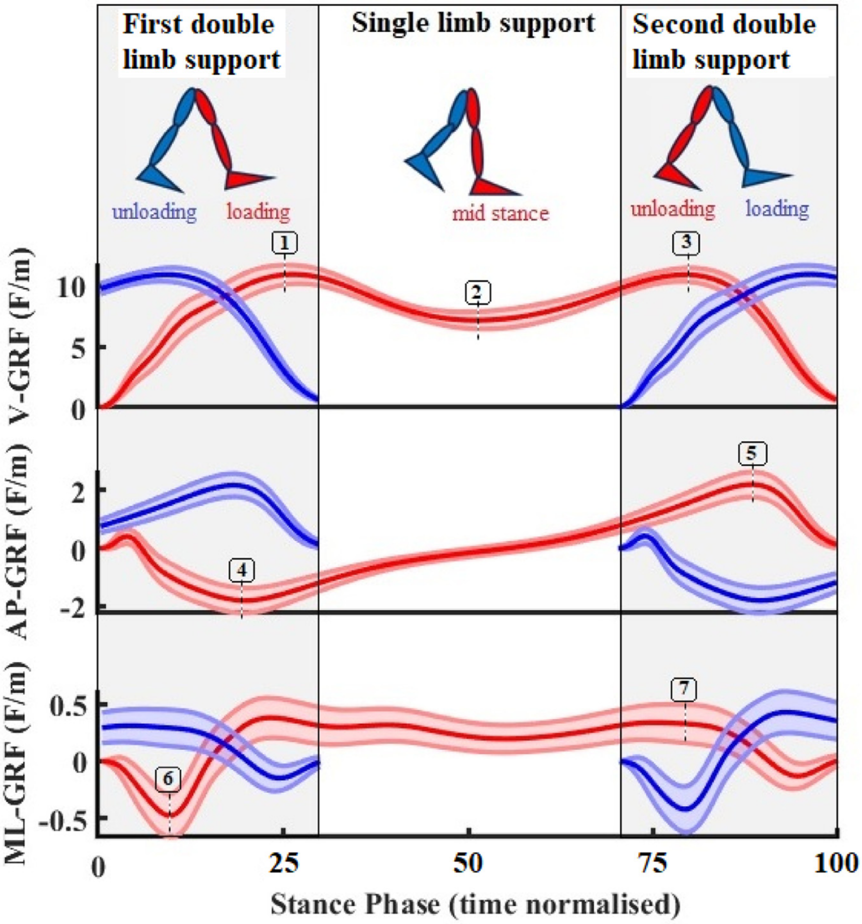

Fig. 1. Three components of mass normalised ground-reaction-forces illustrated with break down into gait subphases. GRFs from opposite limbs illustrated in red and blue curves. 1) peak V-GRF in first double limb, 2) peak V-GRF in single limb, 3) peak V-GRF second double limb, 4) peak AP-GRF in first double limb, 5) peak AP-GRF in second double limb, 6) peak ML-GRF in first double limb, 7) peak ML-GRF in second double limb.

Table 1
Normal and fractured subjects' specifications.

Sr. No	Parameters	Subjects	Age (year)	Mass (kg)	Height (cm)
1	Normal Limb (NL)	70	30.37 ±4.96	71.76 ±13.17	172.69 ±8.23
2	Ankle Fracture (AF)	50	35.96 ±4.49	87.52 ±17.4	176.08 ±7.7
3	Leg Shaft Fracture (AL)	40	38.5 ±7.9	83.32 ±17.11	175.95 ±7.59
4	Calcaneus Foot Fracture (CF)	72	40.05 ±7.9	83.15 ±16.2	178.38 ±6.91
5	Femur or Tibia Fracture (KF)	55	37.45 ±6.39	81.78 ±22.8	174.41 ±9.79
6	Knee Patella Fracture (KP)	28	39.2 ±14.5	82.97 ±18.42	177.57 ±8.1
7	Knee Menisci Rupture (KR)	52	36.12 ±7.97	85.85 ±14.5	175.61 ±9.45

Ankle-related fractures (#2-4), Knee-related fractures (#5-7)

Further, the raw data was sorted based on the participants' age-dependent frequency of occurrence in the bell-shaped curve. It has been widely reported earlier that age variation can cause large deviations in gait assessments [19,20]. Hence, the age-dependent distribution of subjects was tested statistically such that subjects lying within 95% of CI are considered for further analysis and the rest of 5% (both sides of normal distribution) are discarded as outliers. This analysis resulted in the sorting of 19-54 years old adults. The ages of the participants (average±std.) are mentioned in Table 1 for both patients and healthy subjects. The detailed composition of participants is stated in Table 1. The resultant data consisted of three components of GRF (i.e. vertical, AP, and ML) and was extracted for six fractured and one normal walking condition.

Data processing

The raw GRF data was transferred to MATLAB-2022 for subsequent analysis. For each fracture condition, all trials were time normalised to equate the number of samples such that a matrix 200 × X (samples × trials) was obtained per stance phase. The resultant 3D-GRF(s) were cleaned at 10Hz applying a second order low pass Butterworth filter [14,21]. The filtered GRF(s) were then mass normalised following [2,22] to overcome data variation caused by the body masses of participants. These mass normalised-GRF (s) alternatively provide subjects' 3D center-of-mass or trunk acceleration information (force/mass). A comparison of mass normalised signals in Fig. S1 (supplementary materials) revealed that the maximum difference between normal subjects and fractured patients occurs at the peaks of respective 3D-GRF(s). The mass normalised GRF(s) were discretised into three subphases for further analysis. The subphases included the first double-limb support, single-limb support, and second double-limb support periods as illustrated earlier in Fig. 1. For each subphase, the thresholds of GRF(s) i.e., minima and maxima were extracted in MATLAB. Three distinctive peaks were observed and computed from V-GRF (Fig. 1) as a measure of patients' weight-bearing ability during respective subphases. Similarly, the AP and ML GRF(s) exhibited two distinctive peaks (Fig. 1) during each of the first and second double limb support periods, hence, extracted as a measure of patients' balance control in the respective directions. In total, seven data points were extracted for each of the fractured conditions.

Further, gait symmetry was evaluated during both the first and second double limb support periods. During the first double limb support period, the right limb undergoes a weight-loading transition, and the left limb undergoes a weight-unloading transition in parallel and vice versa takes place during the second double limb support. Following that, GRF waveforms of the right and left limbs were statistically correlated to determine gait symmetries during respective double limb support periods.

Data analysis

At first, seven GRF data points extracted for six fractured conditions (AF, AL, CF, KF, KP, KR) and one normal condition (NL) were compared statistically. The statistical computations were executed using SPSS-v20 IBM software. The data was cleaned from outliers by computing interquartile ranges in the SPSS. Then, the Shapiro-Wilk test was applied to check data distribution. Observing non-normal data distribution ($p<0.05$), the Kruskal-Walli's (one-way ANOVA) test was applied along with Bonferroni correction to evaluate the differences between fractured and normal conditions. A difference was considered significant if the p-value was found <0.05.

Gait symmetry was evaluated during both double-limb support periods by applying Spearman's correlation methods. The interlimb correlations were computed between fractured and intact limbs using respective 3D-GRF(s). The correlation coefficient evaluated from normal subjects presents baseline information. Gait asymmetry exists if there is a significant increase or decrease observed in the interlimb correlation of fractured conditions in comparison to baseline.

Considering the fractured side, both ankle and knee fractures illustrated a significant decline ($p<0.001$) in the ranges of 3D normalised GRF(s) during both the first and second double-limb support periods. The mean (±Std.) values of V-GRF(s) as a measure of weight-bearing are presented in Table S1 (supplementary materials) and corresponding plots are shown in Fig. 2. The mean (±Std.) values of AP&ML GRF(s) as a measure of walking stability are presented in Table S2 (supplementary materials) and corresponding plots are shown in Fig. 3. However, the exceptions were observed in V-GRF(s) during single limb support Fig. 2(c, d) and in ML-GRF(s) during the second double limb support period Fig. 3(g, h) which illustrated higher magnitudes than the thresholds evaluated for normal condition (NL).

Lastly, the dependency of the fractured limb on the intact side (gait symmetry) was evaluated through the Spearman correlation method. The correlation coefficients are presented in Table S3 (supplementary materials) and corresponding differences are plotted in Fig. 4. Both ankle and knee fractures illustrated strongly negative correlations between V-GRF(s) of opposite limbs during both the first and second double limb support phases. These correlation coefficients were observed significantly increased in the vertical direction for the fractured conditions compared with a normal limb (NL). The correlation coefficients are presented in Table 3 and corresponding plots are shown in Fig. 4(a, b). In the AP direction, these interlimb correlations were observed to be massively decreased for all fractures in comparison to the normal limb (NL). In the ML direction, only knee fractures illustrated a prompt decrease in Fig. 4(f) in interlimb correlations during the second double limb support phases.

Method validation

The current study introduces methods to quantify key performance indices of rehabilitation among patients undergoing lower limb fractures. These included weight-bearing ability, walking stability, and gait asymmetry and were evaluated here using 3D-GRF data. Patient data was mainly grouped according to the anatomical position of the injury i.e. ankle and knee fractures.

Weight-bearing

In the first double limb support, the outcomes illustrated a significant decrease in the range of V-GRF(s) for all six fracture conditions. This is because, at the earlier stages of rehabilitation, patients struggle with mobility due to poor weight acceptance on the fractured side, fear of imbalance, swelling, and variation in proprioceptive neuromuscular control [7,23]. In a normal gait during the loading response, the plantarflexion moment continues at the ankle and the ankle dorsiflexion moment must resist this torque to prevent foot drop [24]. Whereas, following ankle and knee-related fractures, patients illustrated a decline in ankle plantarflexion

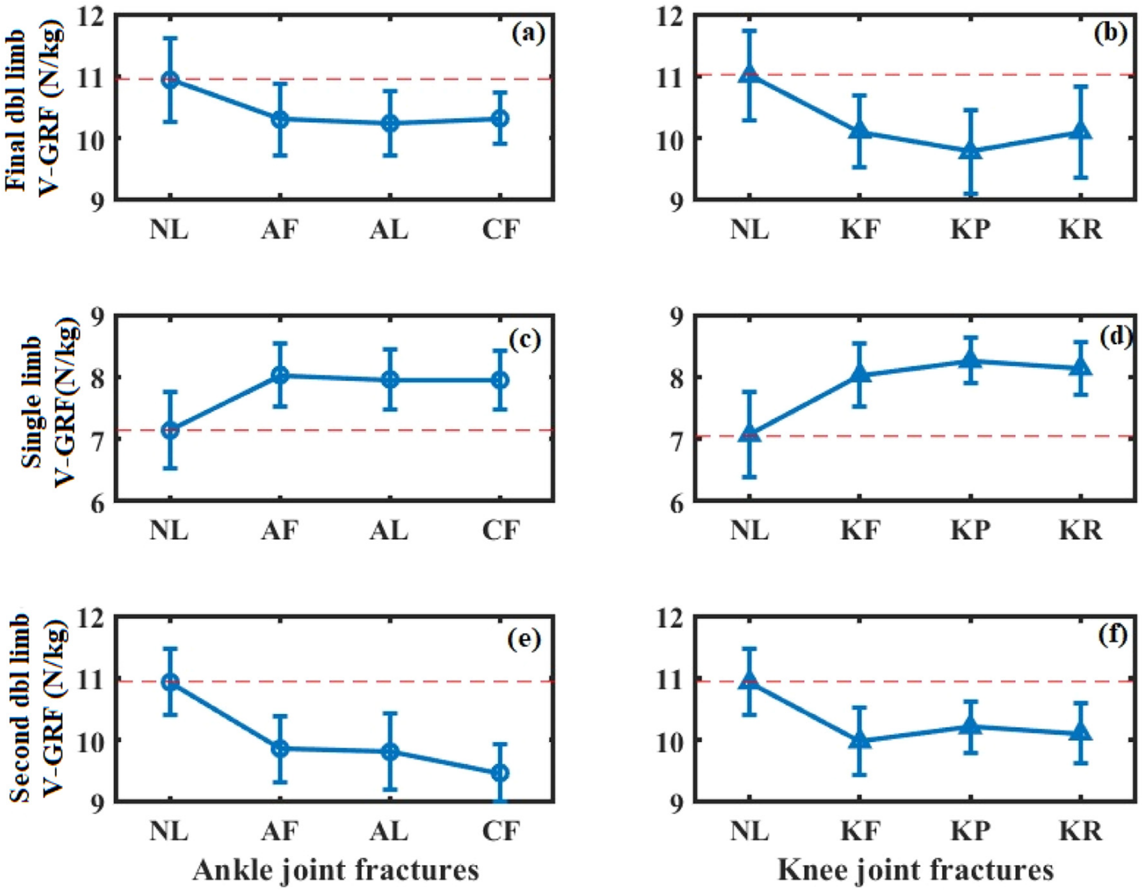

Fig. 2. Fractured limb weight-bearing ability quantified during subphases of a gait cycle. (a, b) first double limb support, (c, d) Single limb support, (e, f) Second double limb support. The left column shows Ankle-related fractures, right column shows Knee-related fractures. All fracture conditions showed a significant decline ($p<0.001$) from baseline. NL: normal limb (baseline), AF: ankle fracture, AL ankle fracture near leg, CF: calcaneus foot fracture, KF: knee tibia fracture, KP: knee patella fracture, KR: kneecap rupture.

and dorsiflexion moments during foot loading [7,25,26] which resulted in the decline of upward trunk motion (i.e., vertical CoM-acceleration (GRF/mass)) compared with the normal limb (NL). An earlier study reinforced this finding by reporting a significant decline in vertical trunk movements following lower limb fractures [7,27]. The main causes of the decrease in vertical trunk/CoM acceleration during the first double limb support period were reduced flexor moments at the affected ankle and knee joints and weakness of lower trunk muscles [7].

In normal gait during single limb support, the GRF moves anteriorly, so a strong dorsiflexion moment at the ankle is produced in a terminal stance. This dorsiflexion moment is opposed by the ankle plantarflexion moment to limit the forward progression of the tibia [24]. However, our results illustrated less decrease in V-GRF during single limb support for all fracture conditions compared with the normal limb (NL). This is because, with fractures, patients move cautiously, and the body generates less downward acceleration in the centre of mass which results in low downward V-GRF(s). During second double limb support, normal subjects execute peak ankle and knee motions (i.e., plantarflexion/flexion) in the unloading phase during which the foot pushes the ground backwards to get lift and move the limb forward [25,26]. Patients with lower-limb fractures showed a significant decline in peak V-GRF(s) during this phase. This is because, patients with fractures were unable to execute plantarflexion moment during late stance [7,14,28]. A prior study also supported this outcome reporting the decrease in overall trunk acceleration following lower-limb fractures [27], however, the variability in trunk acceleration during subphases of a gait cycle was observed unreported previously. In this study, the magnitude of V-GRF(s) illustrated decreasing thresholds during gait subphases which is clinically important to monitor patients' weight-bearing ability and hence progress in fracture recovery.

Further, the outcomes from interlimb correlations between fractured and intact limbs illustrated strongly negative coefficients in the vertical direction. Earlier, the outcomes of interlimb asymmetry were reported as inconsistent for lower limb injuries [4]. In the current study, almost all fracture conditions illustrated a significant increase in interlimb correlations in comparison to normal subjects during both the first and second double limb support phases. Implies, the fractured limbs are greatly dependent on the intact limbs to accept the body weight which also infers greater gait asymmetries. A similar finding was also reported earlier for reduced

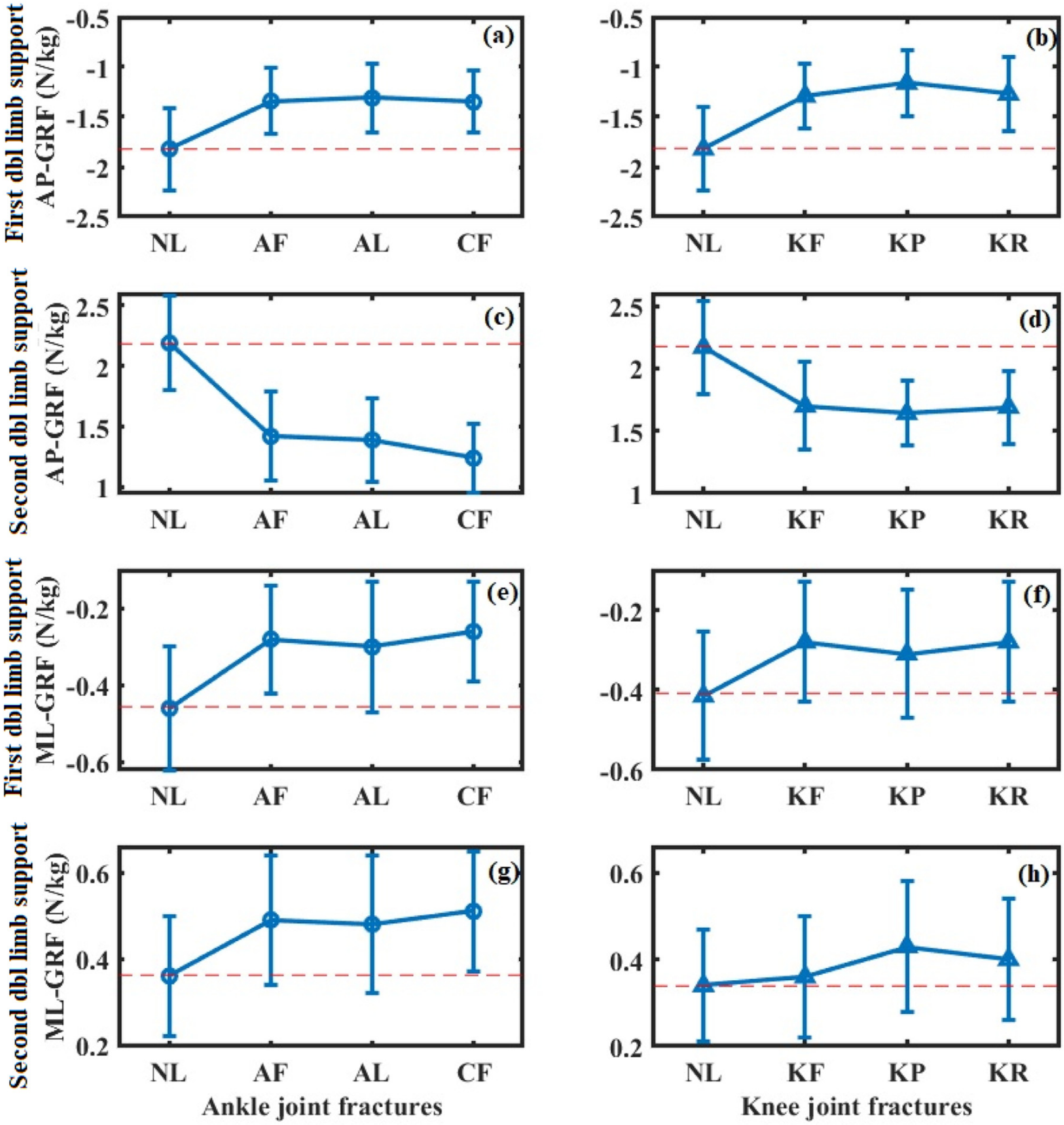

Fig. 3. Fractured limb walking stability quantified during first and second double limb support periods of a gait cycle. The left column shows Ankle-related fractures, right column shows Knee-related fractures. (a-d) mass normalised-GRF(s) in anterior-posterior (AP) direction, (e-h) mass normalised-GRF(s) in medial-lateral (ML) direction. All fracture conditions showed a significant decline ($p<0.001$) from baseline. NL: normal limb (baseline), AF: ankle fracture, AL ankle fracture near leg, CF: calcaneus foot fracture, KF: knee tibia fracture, KP: knee patella fracture, KR: kneecap rupture.

ankle foot motions and intact limbs using CoP-velocity signals [14]. However, the CoP waveforms are limited to predicting walking stability in AP and ML directions and are unable to measure the weight-bearing ability in the vertical direction.

Walking stability

The trunk/CoM movements in AP and ML directions were reported as correlated with the prediction of falls following lower-limb fractures [7,27]. Hence, the thresholds of AP and ML mass normalised GRF(s) (i.e. CoM-acceleration) were computed as a measure of balance control following ankle and knee fractures. All six fracture conditions illustrated a massive decline in the thresholds of GRF(s) during both the first and second double limb support periods. Implies, patients exhibit poor balance control following fractures. Earlier, it was reported that patients with ankle fractures did not exhibit statistical differences in the kinematic ROM(s) i.e.,

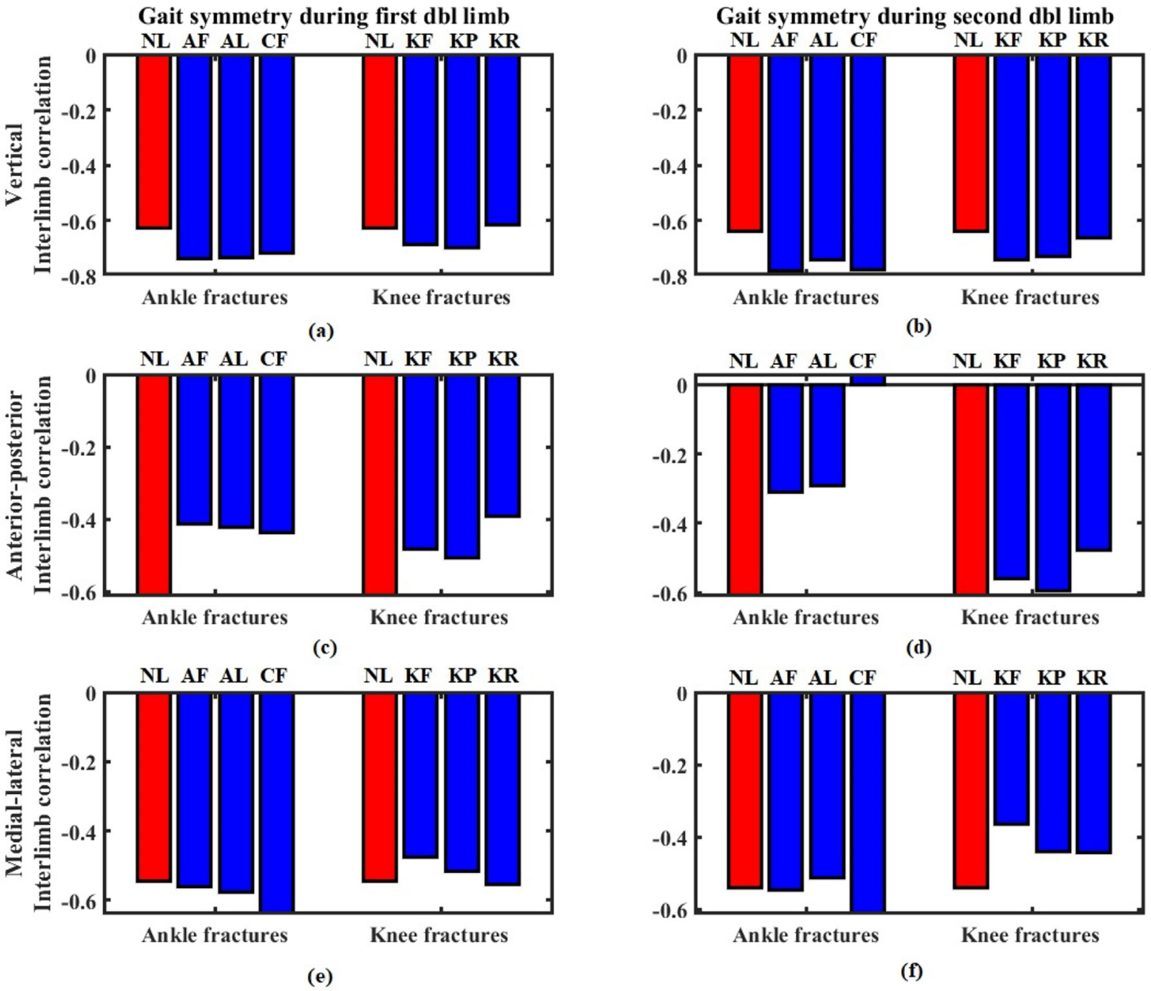

Fig. 4. Gait symmetry computed through the interlimb correlation between opposite limbs GRF(s). The left column shows gait symmetry during the first double-limb support period, and the right column shows gait symmetry during the second double-limb support period. (a, b) weight-bearing dependency in the vertical direction, (c, d) walking stability correlation in the anterior-posterior direction, (e, f) walking stability correlation in the medial-lateral direction. NL: normal limb (baseline), AF: ankle fracture, AL ankle fracture near leg, CF: calcaneus foot fracture, KF: knee tibia fracture, KP: knee patella fracture, KR: kneecap rupture.

abduction/adduction and inversion/eversion angles [7]. In comparison, the kinetic ranges of AP and ML GRF(s) as quantified here provide a quantitative measure of decline in balance control for fractured limbs. Clinically, such quantification is important to assess the severity of a fracture and patient response towards rehabilitation measures.

In the AP direction, almost all fracture conditions illustrated a significant decline in interlimb correlations during both double limb support phases. Implies, patients exhibit greater gait asymmetry in the AP direction compared with normal subjects. In the ML direction, most of the ankle and knee fractures illustrated a significant increase in interlimb correlation during both double limb support periods. This is because fractured patients adopt to walk by keeping their fractured limb static as much as possible. As a result, interlimb correlations between fractured and intact limbs altered significantly in both directions. These findings showed the increased dependency of fractured limbs on the intact side and hence greater gait asymmetries.

In conclusion, the methods of this study illustrated a significant decline in the weight-bearing ability, walking stability, and gait symmetry of patients who underwent ankle or knee-related fractures. This study presents the methods of analysing 3D-GRF(s) to quantify interlimb and intralimb performance indices following lower limb fractures. The intralimb weight-bearing was quantified through vertical GRF(s) and balance control ability was quantified through AP & ML GRF(s) for both fractured and intact limbs. Further, the dependency of the fractured limb on the intact side was quantified through interlimb correlations. As a follow-up of fracture healing, such performance assessments are clinically important to monitor patients' current progress and avoid future complications. It has been reported earlier that weight-bearing exercise with different walking speeds generates different GRFs and loading rates which enhance the nutrient transport and the production of proteoglycan in cartilage leading to a fracture healing process [29-31].

Therefore, future studies should apply current methods to monitor the progress of fracture healing in response to said weight-bearing exercises.

Limitations

Despite the optimisation of fracture restoration evaluations, these methods also have a few limitations. Firstly, the experimental setup used in this study (i.e. force plates) is limited to be used in the lab environment and data can be recorded only for a single stride (gait cycle). Secondly, the force plates are expensive hardware and require special expertise to operate. The force plates are the most accurate equipment available for human movement-related kinetic data acquisition, however, the portable foot insoles are also commercially available as an alternative to acquiring 3D-GRF(s). These insoles are portable, low in cost, and can record GRF(s) for continuous strides with freedom of use outside the lab environment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All supporting data accessible through the Elsevier repository as: 1. Ankle Fractures https://data.mendeley.com/drafts/zh5zjr44zk
2. Knee Fractures https://data.mendeley.com/drafts/8584gn4y37.

Ethical Statement

Ethical approval for data analysed in this research was obtained from the local Ethics Committee of Lower Austria (GS1-EK-4/299-2014) and experiments were conducted after informed consent of the participants.

Credit authors statement

All authors contributed to conceptualization, data curation, formal analysis, methodology, validation, writing original draft, review, and editing. Ms. Tayyaba Sultana also has supervision role.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.mex.2024.102894.

References

[1] I. Mahmood, A. Raza, H.F. Maqbool, A.A. Dehghani-Sanij, Evaluation of an ankle–foot orthosis effect on gait transitional stability during ramp ascent/descent, Med. Biol. Eng. Comput. (2022), doi:10.1007/s11517-022-02587-z.

[2] D. Pfeufer, C. Grabmann, S. Mehaffey, A. Keppler, W. Böcker, C. Kammerlander, et al., Weight bearing in patients with femoral neck fractures compared to pertrochanteric fractures: a postoperative gait analysis, Injury 50 (7) (2019) 1324–1328 https://www.sciencedirect.com/science/article/pii/S0020138319302839.

[3] A.-M. Wu, C. Bisignano, S.L. James, G.G. Abady, A. Abedi, E. Abu-Gharbieh, et al., Global, regional, and national burden of bone fractures in 204 countries and territories, 1990–2019: a systematic analysis from the Global Burden of Disease Study 2019, Lancet Healthy. Longev. 2 (9) (2021) e580–e592, doi:10.1016/S2666-7568(21)00172-0.

[4] Y. Guan, S.S.D. Bredin, J. Taunton, Q. Jiang, N. Wu, D.E.R. Warburton, Association between inter-limb asymmetries in lower-limb functional performance and sport injury: a systematic review of prospective cohort studies, J. Clin. Med. 11 (2) (2022) 360 https://www.mdpi.com/2077-0383/11/2/360.

[5] B. Horsak, D. Slijepcevic, A.-M. Raberger, C. Schwab, M. Worisch, M. Zeppelzauer, GaitRec, a large-scale ground reaction force dataset of healthy and impaired gait, Sci. Data 7 (1) (2020) 143, doi:10.1038/s41597-020-0481-z.

[6] T. Ma, X. Xu, Z. Chai, T. Wang, X. Shen, T. Sun, A Wearable, Biofeedback device for monitoring tibial load during partial weight-bearing walking, IEEE Trans. Neural Syst. Rehab. Eng. 31 (2023) 3428–3436.

[7] M. Mirando, C. Conti, F. Zeni, F. Pedicini, A. Nardone, C. Pavese, Gait alterations in adults after ankle fracture: a systematic review, Diagnostics 12 (1) (2022) 199 https://www.mdpi.com/2075-4418/12/1/199.

[8] L. Yu, Q. Mei, L. Xiang, W. Liu, N.I. Mohamad, B. István, et al., Principal component analysis of the running ground reaction forces with different speeds, Front. Bioeng. Biotechnol. 9 (2021) https://www.frontiersin.org/articles/10.3389/fbioe.2021.629809.

[9] M.F. Vieira, A.A. de Brito, G.C. Lehnen, F.B. Rodrigues, Center of pressure and center of mass behavior during gait initiation on inclined surfaces: a statistical parametric mapping analysis, J. Biomech. 56 (2017) 10–18 https://www.sciencedirect.com/science/article/pii/S0021929017301185.

[10] I. Mahmood, U. Martinez-Hernandez, A.A. Dehghani-Sanij, A model identification approach to quantify impact of whole-body vertical vibrations on limb compliant dynamics and walking stability, Med. Eng. Phys. 80 (2020) 8–17 http://www.sciencedirect.com/science/article/pii/S1350453320300540.

[11] Physio-pedia, https://www.physio-pedia.com/The_Gait_Cycle. 2023 (accessed).

[12] H. Tajdini, Z. Mantashloo, A.C. Thomas, A. Letafatkar, G. Rossettini, Inter-limb asymmetry of kinetic and electromyographic during walking in patients with chronic ankle instability, Sci. Rep. 12 (1) (2022) 3928, doi:10.1038/s41598-022-07975-x.

[13] I. Mahmood, U. Martinez-Hernandez, A.A. Dehghani-Sanij, Evaluation of gait transitional phases using neuromechanical outputs and somatosensory inputs in an overground walk, Hum. Mov. Sci. 69 (2020) 102558 http://www.sciencedirect.com/science/article/pii/S0167945719301708.

[14] I. Mahmood, A. Raza, A.A. Dehghani-Sanij, Evaluation of an adjustable ankle-foot orthosis impact on walking stability during gait transitional phases, Med. Eng. Phys. (2021) https://www.sciencedirect.com/science/article/pii/S135045332100120X.

[15] G. Meyer, M. Ayalon, Biomechanical aspects of dynamic stability, Eur. Rev. Aging Phys. Activity 3 (1) (2006) 29–33, doi:10.1007/s11556-006-0006-6.

[16] S. Bruijn, O. Meijer, P. Beek, J. Van Dieën, Assessing the stability of human locomotion: a review of current measures, J. R. Soc. Interface 10 (83) (2013) 20120999.

[17] A.L. Simon, B. Ilharreborde, P. Souchet, K.R. Kaufman, Dynamic balance assessment during gait in spinal pathologies - a literature review, Orthop. Traumatol. Surg. Res. 101 (2) (2015) 235–246 http://www.ncbi.nlm.nih.gov/pubmed/25765946.

[18] I. Mahmood, H.F. Maqbool, A. Raza, N. Iqbal, A.A. Dehghani-Sanij, Gait dynamic stability evaluation in patients undergoing hip joint fractures – tools to measure rehabilitation effectiveness, Biomed. Phys. Eng. Express. 10 (4) (2024) 045050, doi:10.1088/2057-1976/ad567b.

[19] E.A.F. Ihlen, Age-related changes in inter-joint coordination during walking, J. Appl. Physiol. 117 (2) (2014) 189–198 https://www.physiology.org/doi/abs/10.1152/japplphysiol.00212.2014.

[20] D. Niederer, T. Engeroff, J. Fleckenstein, O. Vogel, L. Vogt, The age-related decline in spatiotemporal gait characteristics is moderated by concerns of falling, history of falls & diseases, and sociodemographic-anthropometric characteristics in 60–94 years old adults, Eur. Rev. Aging Phys. Activity 18 (1) (2021) 19, doi:10.1186/s11556-021-00275-9.

[21] R. Cuisinier, I. Olivier, M. Vaugoyeau, V. Nougier, C. Assaiante, Reweighting of sensory inputs to control quiet standing in children from 7 to 11 and in adults, PLOS One 6 (5) (2011) e19697, doi:10.1371/journal.pone.0019697.

[22] T. Kobayashi, M.W.P. Koh, A. Jor, G. Hisano, H. Murata, D. Ichimura, et al., Ground reaction forces during double limb stances while walking in individuals with unilateral transfemoral amputation, Front. Bioeng. Biotechnol. 10 (2023) https://www.frontiersin.org/articles/10.3389/fbioe.2022.1041060.

[23] Physiopedia (2023) https://www.physio-pedia.com/Foot_and_Ankle_Structure_and_Function. (accessed).

[24] J.B. Webster, B.J. Darter, 4 - principles of normal and pathologic gait, in: J.B. Webster, D.P. Murphy (Eds.), Atlas of Orthoses and Assistive Devices (Fifth Edition), Elsevier, Philadelphia, 2019, pp. 49–62. e1.

[25] S. van Hoeve, J. de Vos, J.P.A.M. Verbruggen, P. Willems, K. Meijer, M. Poeze, Gait analysis and functional outcome after calcaneal fracture, JBJS 97 (22) (2015) https://journals.lww.com/jbjsjournal/Fulltext/2015/11180/Gait_Analysis_and_Functional_Outcome_After.8.aspx.

[26] E. Warmerdam, M. Orth, T. Pohlemann, B. Ganse, Gait analysis to monitor fracture healing of the lower leg, Bioengineering 10 (2023).

[27] C.-Y. Hsu, Y.-S. Tsai, C.-S. Yau, H.-H. Shie, C.-M. Wu, Differences in gait and trunk movement between patients after ankle fracture and healthy subjects, Biomed. Eng. Online 18 (1) (2019) 26, doi:10.1186/s12938-019-0644-3.

[28] L. Bizovska, Z. Svoboda, P. Kutilek, M. Janura, A. Gaba, Z. Kovacikova, Variability of centre of pressure movement during gait in young and middle-aged women, Gait. Posture 40 (3) (2014) 399–402 http://www.sciencedirect.com/science/article/pii/S0966636214005979.

[29] S. Ghimire, S. Miramini, G. Edwards, R. Rotne, J. Xu, P. Ebeling, et al., The investigation of bone fracture healing under intramembranous and endochondral ossification, Bone Rep. 14 (2021) 100740 https://www.sciencedirect.com/science/article/pii/S2352187220305003.

[30] L. Zhang, B.S. Gardiner, D.W. Smith, P. Pivonka, A.J. Grodzinsky, IGF uptake with competitive binding in articular cartilage, J. Biol. Syst. 16 (02) (2008) 175–195 https://www.worldscientific.com/doi/abs/10.1142/S0218339008002575.

[31] L. Zhang, M. Richardson, P. Mendis, Role of chemical and mechanical stimuli in mediating bone fracture healing, Clin. Exp. Pharmacol. Physiol. 39 (8) (2012) 706–710 https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1440-1681.2011.05652.x.