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Emmeline Montané, Camille Cormier, Marino Scandella, Adrian Cangelosi, Philippe Marque, et al.. ToulGaitViz: a tool for the systematic description of lower limb clearance during the swing phase of hemiparetic gait after stroke. A cohort study. *European Journal of Physical and Rehabilitation Medicine*, 2024, 59 (6), pp.669-681. 10.23736/S1973-9087.23.07979-0 . hal-04530870

HAL Id: hal-04530870

<https://ut3-toulouseinp.hal.science/hal-04530870v1>

Submitted on 4 Sep 2024

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ORIGINAL ARTICLE

ToulGaitViz: a tool for the systematic description of lower limb clearance during the swing phase of hemiparetic gait after stroke

A cohort study

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ABSTRACT

BACKGROUND: In post-stroke hemiparetic subjects, a systematic and quantified description of the shortening default and compensatory movements during the swing phase of gait is essential to guide treatments and assess the impact of therapeutic interventions. However, such a systematic approach does not exist in the current clinical practice.

AIM: The aim of this study was to present a method improving the quantification and visualization of the kinematics of both lower limbs during the swing phase of gait, more specifically the origin of shortening default and the weight of compensations, based on a tool specifically developed: ToulGaitViz.

DESIGN: Observational cohort study.

SETTING: Three-dimensional kinematic gait analyses of outpatients evaluated in Toulouse university hospital.

POPULATION: ToulGaitViz was applied to 151 post-stroke hemiparetic participants and 48 healthy control participants.

METHODS: ToulGaitViz is a standalone software allowing to compute 1) limb clearance as the sum of the shortening related to hip, knee and ankle flexion in the sagittal plane; 2) compensations related to the abduction of the limb and hip hiking at mid-swing. Both centimetric and angular values of the clearance were reported as well as their correlations with walking speed.

RESULTS: Overall, the contribution of compensations in clearance was higher in post-stroke hemiparetic subjects than in healthy control participants with both centimetric (130% vs. 33%; $P < 0.001$) and angular methods (23% vs. 1.4%; $P < 0.001$). The centimetric method better represents the specific contribution of each segment to the clearance than the angular method. Symbolically, mean kinematic data from the cohort supports the claim that 2° of pelvic obliquity is equivalent to 10° of knee flexion to increase clearance by 1 cm, emphasizing the non-proportionality between the angular values and the actual contribution to the shortening. ToulGaitViz allows visualization of clearance, segmental shortening and compensation evolution before and after any therapeutic intervention with quantitative and comprehensive data.

CONCLUSIONS: The ToulGaitViz could be systematically used in clinical practice to extract relevant kinematic data from the origin of shortening default and the weight of compensations.

CLINICAL REHABILITATION IMPACT: This tool allows better understanding of the mechanisms of action of treatments to better link them to the subjects' needs.

(Cite this article as: Montané E, Cormier C, Scandella M, Cangelosi A, Marque P, Moissenet F, et al. ToulGaitViz: a tool for the systematic description of lower limb clearance during the swing phase of hemiparetic gait after stroke. A cohort study. Eur J Phys Rehabil Med 2023;59:669-81. DOI: 10.23736/S1973-9087.23.07979-0)

KEY WORDS: Gait analysis; Hemiplegia; Neurologic gait disorders; Biomechanical phenomena.

Following stroke, two out of three people experience difficulties in achieving gait¹ which is often represented by a default in paretic lower limb shortening. This impairment can result in difficulty moving the limb forward and a lack of limb clearance favoring falls.² It can be partly related to muscle paresis and/or overactivity^{3, 4} and is the target of many treatments such as orthopedic surgery, neurosurgery, botulinum toxin, orthotics or rehabilitation.^{5, 6}

Physiologically, limb clearance during swing results from hip flexion, knee flexion and ankle dorsiflexion.⁷ In post-stroke subjects with hemiplegia, clearance of the paretic limb results from a combination of impaired limb shortening movements and compensatory movements.⁸ Several compensation strategies are commonly observed such as increased knee or hip and knee flexion (*i.e.*, a step-gait), elevation of the pelvis on the paretic side (*i.e.*, hip hiking), overall elevation of the pelvis secondary to contralateral vaulting, circumduction movement of the lower limb allowed by a hip abduction or increased foot progression angle.⁹

In previous studies and in usual clinical practice, limb clearance is described by hip, knee and ankle sagittal joint angles for limb shortening movements and compensatory movements by pelvic obliquity and hip abduction.¹⁰ In particular, the angular method for computing clearance is convenient to measure the decrease (*i.e.*, the impairment) or the increase (*i.e.*, the compensation) of the range of motion of the joints during swing compared to healthy subjects. However, as joint kinematics is dependent on speed, gender, age and body mass index,¹¹ the direct comparison of joint angles obtained from post-stroke and healthy subjects is not relevant. Moreover, the sum of joint flexions in the sagittal plane (shortening) is not comparable to the sum of joint abductions in the frontal plane (compensation) and cannot be cumulated.¹² However, despite its potential clinical interest, the lack of proportionality between the degrees of shortening in the sagittal plane and in the frontal plane is not known. Another approach is to define limb clearance with a centimetric method, *e.g.* using the hip-toe distance¹³ or the pelvis-toe distance.¹² However, these values do not enable us to evaluate the role of compensation nor the contribution of each segment in limb clearance. Yet the knowledge of this contribution could allow us to better target and follow-up the neuro-orthopedic intervention.

The objectives of this study were:

- to propose a new method of centimetric quantification for lower limb clearance related to pelvis, hip, knee and ankle kinematics as well as associated compensatory movements;

- to incorporate this method into a standalone software, ToulGaitViz (<https://tinyurl.com/ToulGaitViz>), that allows the community to easily reproduce the method on research or clinical datasets;

- to evaluate the method on a dataset established from healthy control participants and post-stroke hemiparetic participants' recordings: 1) by comparing the lower limb kinematic characteristics of these populations; 2) by assessing the ratio between the clearance computed using the angular and centimetric methods; 3) by assessing the relationship between walking speed, raw limb clearance and kinematic; 4) by assessing the bias of the model.

Materials and methods

Study design

A retrospective and observational monocentric study based on the analysis of routine care data was conducted at a French University Hospital. Subjects who had experienced a stroke received information about anonymized data collection and the study was registered (registration number: RnIPH 2020-47) and covered by MR-004 (CNIL number: 2206723 v0) in accordance with French Ethics and Regulatory Law (Public Health Code).

Data of healthy control participants were extracted from an opensource dataset of 3D Gait Analyses (3DGAs) conducted in Rehazenter, Luxembourg and previously published.¹⁴ Healthy control participants were recruited on a voluntary basis. The study was approved by the Rehazenter Institutional Medical Ethics Committee and follows the recommendations of the Declaration of Helsinki.

Participants

Population and sample size

Adults with hemiparesis following stroke were recruited at Toulouse University Hospital during their routine care pathway for neuro-orthopedic management. Based on sample size formulas of cross-sectional studies¹⁵ and the standard deviation of toe clearance proposed by Pongpipatpaiboon *et al.*,¹⁶ we estimated that, for an alpha value of 0.05 and a risk of error of 3%, the number of participants needed to be representative of the population was 136.¹⁷

A sample of 48 healthy control participants was extracted from the Schreiber 2019 opensource dataset which was sufficient to consider data and its 95% confidence interval as a normative basis.¹⁸

Inclusion/exclusion criteria

Inclusion criteria for post-stroke participants were: 1) to have hemiparesis following ischemic or hemorrhagic stroke; 2) to have carried out a 3DGA at Toulouse University Hospital between November 2011 and June 2022; 3) to be at least 18 years old at the time of the 3DGA; 4) not to be opposed to the data collection. Only the first 3DGA was kept for participants who performed several 3DGAs during this period except if it was performed after a neuro-orthopedic intervention. However, to illustrate the significance of ToulGaitViz tool in clinical practice, an example of a second 3DGA performed after a neuro-orthopedic intervention has been included for 1 post-stroke participant. Exclusion criteria were: 1) to have cerebellar or proprioceptive ataxia with a gait impact; 2) to have a history of orthopedic surgery of the lower limb with a gait impact; 3) to have performed the 3DGA with orthopedic shoes or apparatus that did not allow ankle or knee movement analysis; or 4) to have bilateral paresis.

Healthy control participants were asymptomatic and injury-free for both lower and upper extremities in the most recent six months with no lower or upper extremity surgery within the last two years. Furthermore, only participants with a leg length difference lower than 1.5%

of height (corresponding to a maximum of 0.03 m) were included in this study to avoid leg length discrepancy affecting the dataset.¹⁴

Dataset

Procedure

The 3DGA of post-stroke participants was performed at the Gait Analysis Laboratory in Toulouse University Hospital. Participants walked at a self-selected speed along a 10 m walkway and completed 14 recorded trials. Fifty subjects (Table I) used a cane during 3DGA because they were unable to walk safely without.

Data records

The 3D trajectories of a set of reflective cutaneous markers were recorded using 8 optoelectronic cameras sampled at 60 Hz from 2011 until March 2017 (Vicon MCam-2, Vicon Oxford Metrics, UK) and at 100 Hz after (Vicon Vantage V5, Vicon Oxford Metrics, Oxford, UK). This marker set followed the lower limb Vicon Plug-in Gait model (Vicon Oxford Metrics).¹⁹ Three-dimensional ground reaction forces and moments were recorded using 2 force plates embedded into the walkway (OR6-7, AMTI, USA)

TABLE I.—Clinical and spatiotemporal gait characteristics of post-stroke participants (N.=151) and healthy control participants (N.=48).

Characteristics	Post-stroke (N.=151)	Healthy controls (N.=48)
Clinical characteristics		
Male gender	78 (51.7%)	25 (52%)
Age (years), mean (SD)	50.4 (14.3%)	36.6 (13.2%)
Height (cm), mean (SD)	167.7 (9.7%)	173.9 (9.4%)
Weight (kg), median (min to max)	73.3 (39.4 to 132.0)	72.1 (50.0 to 98.0)
Stroke delay (months), median (min to max)	52 (3 to 495)	NA
Stroke type (N.=151)		
Ischemic	89 (58.9%)	NA
Hemorrhagic	62 (41.1%)	NA
Left hemiparesis	76 (50.3)	NA
FAC (/8; N.=120), median (min to max)	6 (4 to 8)	NA
Paretic side EVGS (/34; N.=145), median (min to max)	9 (1 to 23)	NA
Non-paretic side EVGS (/34; N.=145), median (min to max)	3 (0 to 15)	NA
Use of a cane during 3DGA		
Single cane	50 (33.1)	NA
Elbow crutch	34 (22.5)	NA
Tripod cane	9 (6.0)	NA
	7 (4.6)	NA
Spatiotemporal gait characteristics, mean [95% CI]		
Walking speed (m/s)	0.55 [0.50;0.59]	1.16 [1.12;1.20]
Spatial asymmetry	6.0 [3.1;10.1]	-0.67 [-1.38;0.03]
Temporal asymmetry	-18.6 [-20.2;-17.0]	0.44 [0.15;0.73]
Stride length (cm)	0.79 [0.75;0.84]	1.28 [1.24;1.31]
Cadence (steps/min)	78.9 [75.7;82.1]	108.5 [105.9;111.0]
Stride width (cm)	14.9 [14.0;15.8]	9.0 [8.3;9.7]

FAC: functional ambulation classification; EVGS: Edinburgh Visual Gait Score; 3DGA: 3D kinematic gait analysis; NA: not applicable.

and sampled at 2000 Hz with no filtering. This dataset was completed with sagittal and frontal videos, clinical data (*i.e.*, age, gender, stroke etiology, elapsed time from stroke onset, use of a cane during 3DGA, modified Functional Ambulation Classification²⁰ and Edinburgh Visual Gait Score)²¹ and anthropometric data (*i.e.*, body mass, height and bilateral knee and ankle width as well as leg length). All data was collected by the same operator (MS).

Data pre-processing

Marker trajectories were gap-filled using the Woltring method²² and filtered using a Bezier spline interpolation filter.²³ If force plate data were available, gait events (*i.e.*, foot strike and foot off) were defined automatically with operator verification. Conversely, in the absence of data from the force plate (use of a cane, length of steps too short), gait events were defined manually by the operator using marker trajectory and video data. Spatiotemporal parameters as well as bilateral lower limb joint centers and kinematics were computed through the Vicon Plug-in Gait pipeline. All data were finally exported, for each participant's trial, in the standard c3d file format (<https://www.c3d.org>). All data pre-processing was performed using Workstation software before March 2017 (v.4.7, Vicon Oxford Metrics) and Nexus software afterwards (v.2.9.3, Vicon Oxford Metrics).

Data reduction

Gait cycle data for each trial was imported and processed with a custom-made MATLAB (version R2021a, MathWorks, Natick, MA, USA) script using the Biomechanical ToolKit (BTK).²⁴ Ankle, knee, hip and pelvis kinematics were extracted as well as the coordinates of the hip, knee and ankle joint centers and spatiotemporal parameters (*i.e.*, walking speed, step length, stride width, cadence and duration of single limb stance). Temporal (from unipedal stance relative duration) and spatial (from step length) asymmetries were then computed with the following formula:

$$\text{Asymmetry Index} = 100 \times \frac{(V_{\text{Paretic}} - V_{\text{NonParetic}})}{(V_{\text{Paretic}} + V_{\text{NonParetic}})}$$

where V_{Paretic} and $V_{\text{NonParetic}}$ were the value of a gait variable recorded for the paretic and non-paretic limb respectively. Asymmetry indexes ranged from -100 to 100, a value of zero indicating perfect symmetry and a positive (negative) index indicating a larger value of the gait variable for the paretic (non-paretic) leg.²⁵ For asymmetry indexes in healthy control participants, the paretic side and

non-paretic side values have been replaced by left and right side values respectively.

Kinematic data of each gait cycle was interpolated over 1000 points. Outliers were identified by the interquartile range (IQR) method (*i.e.*, data outside the first quartile minus $1.5 \times \text{IQR}$ and the third quartile plus $1.5 \times \text{IQR}$ were excluded)²⁶ from the following data: maximal hip, knee and ankle flexion angles during the swing phase. All the kinematic and spatiotemporal variables in relation to these outlier cycles were removed from analysis. All other variables (*i.e.*, walking speed, step length, stride width, cadence, duration of single limb stance) were stored, averaged and checked by two independent investigators (EM and DG) to avoid discrepancies.

ToulGaitViz

Presentation

ToulGaitViz is a standalone software created with MATLAB (version R2019a, MathWorks) (download here: <https://tinyurl.com/ToulGaitViz>). It provides a synthetic two-part graphical representation of the kinematic data from a 3DGA (Figure 1). The first part is related to the quantification of limb clearance using the angular and centimetric methods at mid-swing, including a representation of the respective contributions of the pelvis, hip, knee and ankle to shortening and compensation strategies. The second part is related to a synthetic visualization of key shortening and compensation biomarkers in comparison to a participant-adjusted norm obtained from previously published regressors.¹¹

Quantification of limb clearance at mid-swing

Paretic limb clearance was assessed at mid-swing when the paretic toe marker was under the hip joint center during the swing phase¹⁶ which is defined as the critical moment of limb clearance during this phase.⁷ Three biomarkers of limb clearance were computed (Figure 1A, 2):

- raw limb clearance (expressed in centimeters) was defined as the vertical position of the toe marker at mid-swing. As the toe marker indirectly represents the actual raw limb clearance, the raw limb clearance was corrected by removing the offset corresponding to the minimal distance between the toe marker and the floor during the previous stance phase;
- angular limb clearance index ($\text{Clearance}_{\text{DEG}}$, expressed in degrees) was defined as the sum of an angular shortening index ($\text{Short}_{\text{DEG}}$) and an angular compensation index (Comp_{DEG}). The angular shortening index was determined

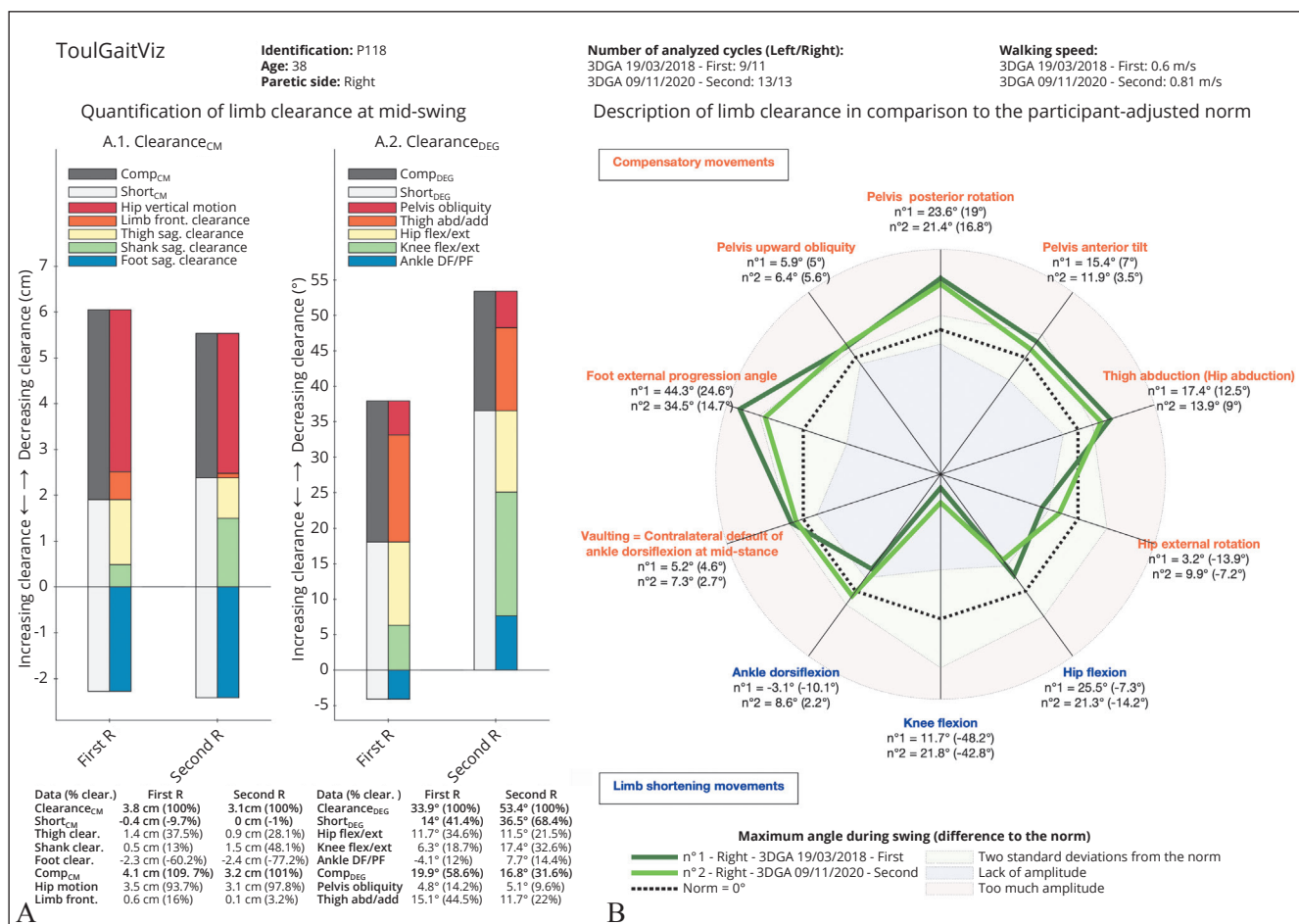


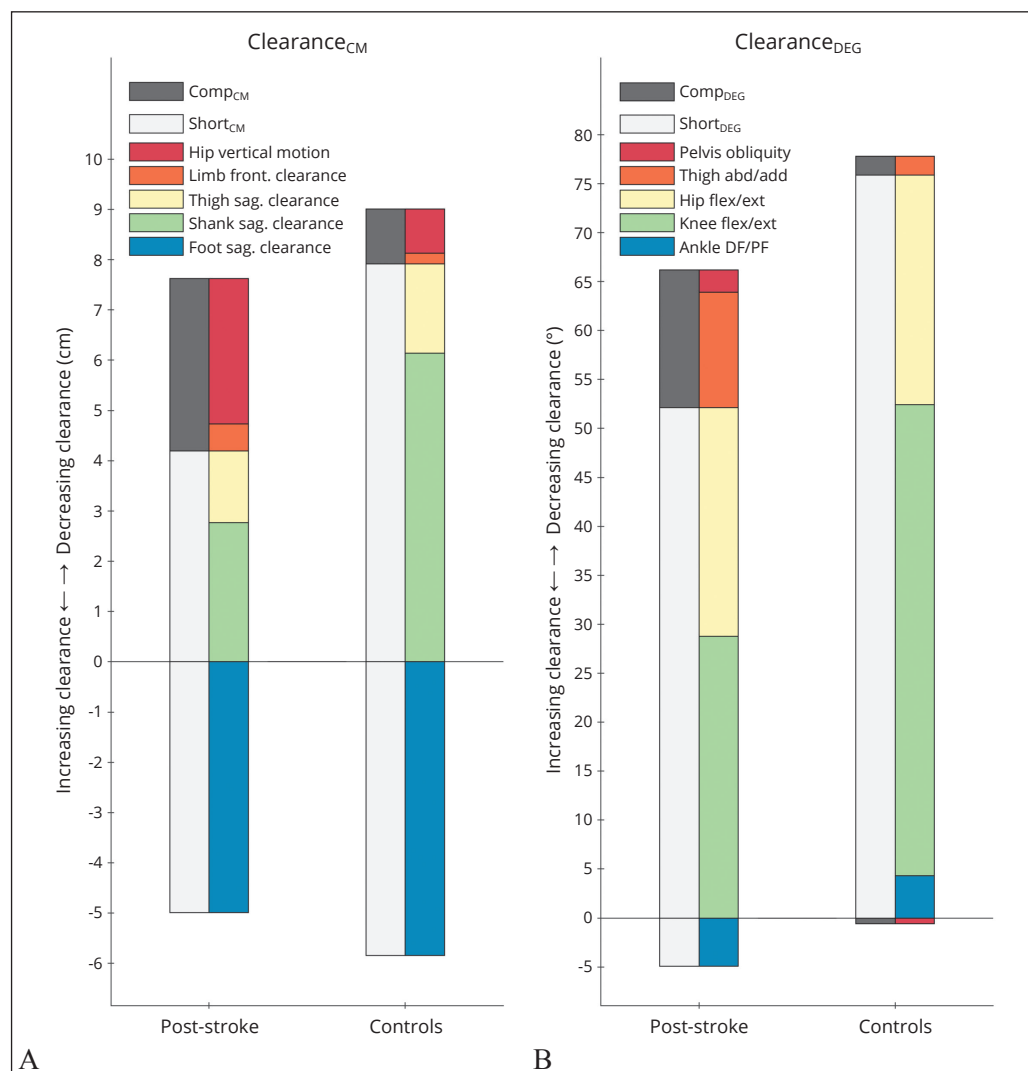
Figure 1.—ToulGaitViz of P118 participant for two 3DGAs performed before and after a neurotomy of the soleus nerve, lengthening of the gastrocnemius muscle and toe claw surgery. Only the right limb is represented. A) Quantification of limb clearance at mid-swing represented by histograms and table of corresponding data (including the respective contribution of each component expressed in percentage of limb clearance). A1) Clearance_{CM}: positive values correspond to increasing clearance; negative values correspond to decreasing clearance. The left part of the histogram shows the index of Short_{CM} and Comp_{CM} while the right part shows the segmental clearance taking part into the limb clearance. A2) Clearance_{DEG}: positive values correspond to increasing clearance in relation to upward obliquity for pelvis/hip abduction (from frontal thigh angle to the vertical), hip and knee flexion and ankle dorsiflexion; negative values correspond to decreasing clearance in relation to pelvis downward obliquity, hip adduction, knee recurvatum and ankle plantarflexion. The left part of the histogram shows the index of Short_{DEG} and Comp_{DEG} while the right part shows the joint clearance taking part into the limb clearance. B) Description of limb clearance in comparison to the participant-adjusted norm. The bold lines represent the difference to the norm of the corresponding peak joint angle during swing for the first 3DGA (dark green in the online version) and the second one (light green in the online version). The dashed bold line represents the participant-adjusted expected norm. The green interval corresponds to 2 standard deviations of the participant-adjusted expected norm (cf. methods for details on the custom expected norm). The peak angle during swing (difference to the norm) is detailed for each movement description. A value in the center of the graph (blue in the online version) represents a lack of joint amplitude. A value at the edge of the graph (red in the online version) is a movement carried out over its norm (compensatory movement). The movements of the joints that are written in blue in the online version are expected to be limb shortening movements and the ones written in orange are expected to be compensatory movements.

in the sagittal plane and corresponds to the sum of hip flexion, knee flexion and ankle dorsiflexion/plantarflexion angles at mid-swing. The angular compensation index was determined in frontal plane and corresponds to the sum of pelvic obliquity and thigh abduction angles at mid-swing;

- centimetric limb clearance index (Clearance_{CM}, expressed in centimeters) was defined as the sum of a cen-

timetric shortening index (Short_{CM}) and a centimetric compensation index (Comp_{CM}). The centimetric shortening index was determined in the sagittal plane and corresponds to the sum of thigh, shank and foot shortening. The centimetric compensation index was determined in the frontal plane and corresponds to the sum of hip hiking and thigh and shank shortening. Details related to segment

Figure 2.—Quantification of limb clearance at mid-swing in the cohort of post-stroke ($N=151$) and control ($N=48$) subjects. A) $Clearance_{CM}$: positive values correspond to increasing clearance; negative values correspond to decreasing clearance. The left part of the histogram shows the index of $Short_{CM}$ and $Comp_{CM}$ while the right part shows the segmental clearance taking part into the limb clearance. B) $Clearance_{DEG}$: positive values correspond to increasing clearance in relation to upward obliquity for pelvis/hip abduction (from frontal thigh angle to the vertical), hip and knee flexion and ankle dorsiflexion; negative values correspond to decreasing clearance in relation to pelvis downward obliquity, hip adduction, knee recurvatum and ankle plantarflexion. The left part of the histogram shows the index of $Short_{DEG}$ and $Comp_{DEG}$ while the right part shows the joint clearance taking part into the limb clearance.



shortening are given in the Supplementary Digital Material 1 (Supplementary Text File 1);

- the respective contribution of the compensation ($Comp_{CM}$ and $Comp_{DEG}$) and the shortening ($Short_{CM}$ and $Short_{DEG}$) indexes were defined as a percentage of angular ($Clearance_{DEG}$) or centimetric ($Clearance_{CM}$) limb clearance ($\%Comp$ and $\%Short$). Values of $\%Short$ and $\%Comp$ were between $-\infty$ and $+\infty$ (high values especially when the clearance values were close to 0).

The same methodology was applied to the dataset of healthy control participants on both legs.

Five ratios of segment clearance over respective joint clearance ($cm/^\circ$) were computed to describe proportional-ity between the centimetric and the angular clearance.

Description of limb clearance in comparison to the participant-adjusted norm

To describe paretic limb progression during the swing phase, 10 biomarkers were presented on the same radar chart in relation to their normative value. The difference between the actual and normative values was expressed in degrees. A negative value represents a default of movement and a positive value an excess of movement.

Limb shortening default is represented by a negative difference to the norm of the hip, the knee or ankle flexion.

Compensatory movements are defined as a positive difference to the corresponding norm and were defined as: stepping in case of increased flexion of the hip or knee, hip

hiking in case of pelvis upward obliquity, a pelvis posterior rotation, a pelvis anterior tilt, a thigh abduction from a vertical reference, a hip external rotation, an external rotation of foot progression angle and vaulting in case of contralateral default of ankle dorsiflexion at mid-stance.

Walking speed, body mass index, age and gender were used to predict subject-specific and velocity-specific normative angular values for hip, knee and ankle sagittal flexion.¹¹ Standard deviation values for hip, knee and ankle peak flexion were obtained from data published by Schreiber *et al.*¹⁴ For other kinematic parameters not velocity dependent (pelvic upward obliquity, pelvic posterior rotation, pelvic anterior tilt, thigh abduction, hip external rotation and foot progression angle), normative data were also obtained from data published by Schreiber *et al.*¹⁴ For each dataset, a difference greater than ± 2 SD compared to the mean norm (negative if shortening default and positive if compensation were present) was considered relevant (Figure 2B). For multiple 3DGA representation, the largest standard deviation of each biomarker was represented.

Statistical analysis

Data normality was verified by employing the Kolmogorov-Smirnov Test using the Lilliefors correction ($P > 0.05$ if normal distribution), Kurtosis and Skewness tests. Quantitative participant characteristics were described by mean and standard deviation (SD). Ordinal parameters were described by median, minimal and maximal values. Qualitative parameters were described by number (n) and percentage (%). Kinematic and spatiotemporal parameters were described by the mean and its 95% confidence interval. If kinematic data were missing, the participant was not included in the analysis. Missing clinical data were reported in the results tables and analyses were performed on available data.

The median, first and third quartiles of $Clearance_{CM}$, $Short_{CM}$, $Comp_{CM}$, $\%Comp_{CM}$, $Clearance_{DEG}$, $Short_{DEG}$, $Comp_{DEG}$ and $\%Comp_{DEG}$ were described and graphically illustrated, highlighting segmental and joint contributions for both post-stroke and healthy control participants. Some of these parameters did not have a normal distribution so the non-parametric Wilcoxon Rank Test was used.

The five ratios of joint clearance over respective segment clearance were compared using the Friedman test as their distribution was not normal. The Wilcoxon Test for paired data was used for *post-hoc* tests.

Spearman correlations (r) were computed between $Clearance_{CM}$, $Clearance_{DEG}$, $Comp_{CM}$, $Comp_{DEG}$, $\%Comp_{CM}$ and $\%Comp_{DEG}$ on the one hand and walking speed as

well as raw limb clearance on the other hand. Correlations were considered very strong if $r \geq 0.8$, strong if $0.6 \leq r < 0.8$, moderate if $0.4 \leq r < 0.6$, and weak if $r < 0.4$.²⁷

To avoid family-wise type I error inflation due to repetition of statistical tests, a Bonferroni procedure was used to set the level of significance at $P < 0.005$ for two-sample *t*-test ($N = 10$) and Friedman *post-hoc* Wilcoxon tests ($N = 10$) and at $P < 0.004$ for Spearman correlations ($N = 12$).

Raw limb clearance was compared to the $Clearance_{CM}$ with a Bland-Altman graph to investigate the bias between these two outcomes. A significant bias was retained if the confidence interval of the mean difference did not include zero.

Statistical analysis and graphical representations were performed with MATLAB (version R2021a, MathWorks).

Data availability statement

Data are available on reasonable request from the corresponding author (Supplementary Digital Material 2: Supplementary Table I).

Results

Participants

One hundred and fifty-one 3DGAs of post-stroke participants and 48 3DGAs of healthy control participants were included in this study (Supplementary Digital Material 3: Supplementary Figure 1). The mean and range number of cycles analyzed for each participant was 11.4 (3 to 19) after excluding a mean (min. to max.) of 10.5% (0% to 40%) cycles per participant. The clinical and spatiotemporal gait characteristics of post-stroke and healthy control participants are reported in Table I.

ToulGaitViz

The use of ToulGaitViz on one post-stroke participant (Figure 1) illustrates the quantification of limb clearance at mid-swing in centimeters and in degrees (part A). It also shows the description of limb clearance in comparison to the participant-adjusted norm (part B) based on ten biomarkers of limb shortening or compensatory movements. Important characteristics such as participant identification, age, paretic side and date of 3DGA are presented in the upper part. This information is required by the Matlab ToulGaitViz code to run the script. The other required information are height, weight and gender in order to adapt the norm with relevant regressors.¹¹ The software then

requires the .c3d files of each 3DGA needed to analyze and asks the user which side to display. ToulGaitViz can display both limbs of up to three different 3DGAs, making it possible to compare evolution over time or before/after any therapeutic intervention. As an example, Figure 1 illustrates the significance of ToulGaitViz applied to a participant who performed two 3DGAs before and after a neurotomy of the soleus nerve, lengthening of the gastrocnemius muscle and toe claw surgery. It is noticeable that walking speed after the surgery had increased by 0.21 m/s (Supplementary Digital Material 4: Supplementary Text File 2).

Ratios between centimetric and angular methods for limb clearance computation

Ratios between centimetric and angular methods for limb clearance computation are presented in Table II. Ratios have been calculated from the data of both limbs in both groups (N.=398). The Friedman test showed a significant

difference between the variance of ratios per joint. Significant differences ($P<0.005$) between group are summarized in Table II. It underlines the non-proportionality of clearance comparison between joints and planes when using the angular method.

Application of ToulGaitViz in a post-stroke population compared to healthy controls

Quantification of limb clearance at mid-swing in a post-stroke population

Figure 2 shows the Clearance_{CM}, the Clearance_{DEG}, the Short and the Comp index details applied to a post-stroke population and compared to a healthy control population. Data from the indexes are presented and compared between populations in Table III. Each post-stroke participant's data as compared to the data of the healthy control participants are presented in Supplementary Digital Material 5 (Supplementary Figure 2).

TABLE II.—Ratio between limb clearance computed using the centimetric and the angular methods and comparison between groups by post-hoc Wilcoxon Rank Test.

Segment/ joint	Ratio cm/°, mean±SD	Hip hiking/ pelvis obliquity	Limb/ thigh abduction clearance in frontal plane	Thigh/ hip clearance in sagittal plane	Shank/ knee clearance in sagittal plane	Foot/ ankle clearance in sagittal plane
Hip hiking/pelvis obliquity	0.57±5.17	-	<0.001*	<0.001*	<0.001*	<0.001*
Limb/thigh abduction clearance in frontal plane	0.1±0.13	-	-	<0.001*	<0.001*	<0.001*
Thigh/hip clearance in sagittal plane	0.07±0.05	-	-	-	0.013	<0.001*
Shank/knee clearance in sagittal plane	0.11±0.04	-	-	-	-	<0.001*
Foot/ankle clearance in sagittal plane	-0.38±7.46	-	-	-	-	-

Data are mean±SD in cm/deg for N.=398, including both limbs of post-stroke participants and healthy control participants. The value represents the amount of clearance in centimeters corresponding to a degree of clearance. These results show the non-proportionality of the angular limb clearance between joints/segments and planes of analysis. For example, a gain of 10 degrees in pelvic obliquity provides 5.7 cm of shortening whereas 10 degrees of knee flexion provides 1.1 cm of clearance. *Statistically significant if $P<0.005$.

TABLE III.—Index of clearance, shortening and compensation by centimetric method and angular method in post-stroke participants and healthy control participants.

Median [Q1;Q3]	Post-stroke (N.=151)	Controls (N.=48)	P value*
CM			
Clearance _{CM} (cm)	2.65 [1.65;3.58]	3.02 [2.64;3.75]	<0.001
Short _{CM} (cm)	-0.83 [-1.65;0.15]	2.07 [1.59;2.73]	<0.001
%Short _{CM} (%)	-29.77 [-79.44;7.52]	66.92 [55.23;76.48]	<0.001
Comp _{CM} (cm)	3.44 [2.13;4.52]	1.03 [0.73;1.39]	<0.001
%Comp _{CM} (%)	129.77 [92.48;179.44]	33.08 [23.52;44.77]	<0.001
DEG			
Clearance _{DEG} (deg)	62.95 [44.01;77.57]	77.57 [73.57;82.76]	<0.001
Short _{DEG} (deg)	45.86 [31.28;63.81]	76.59 [71.45;81.55]	<0.001
%Short _{DEG} (%)	76.59 [63.3;85.85]	98.57 [96.47;100.23]	<0.001
Comp _{DEG} (deg)	13.9 [8.41;19.6]	1.07 [-0.17;2.7]	<0.001
%Comp _{DEG} (%)	23.41 [14.15;36.7]	1.43 [-0.23;3.53]	<0.001

*Significant threshold after Bonferroni correction is $P<0.005$.

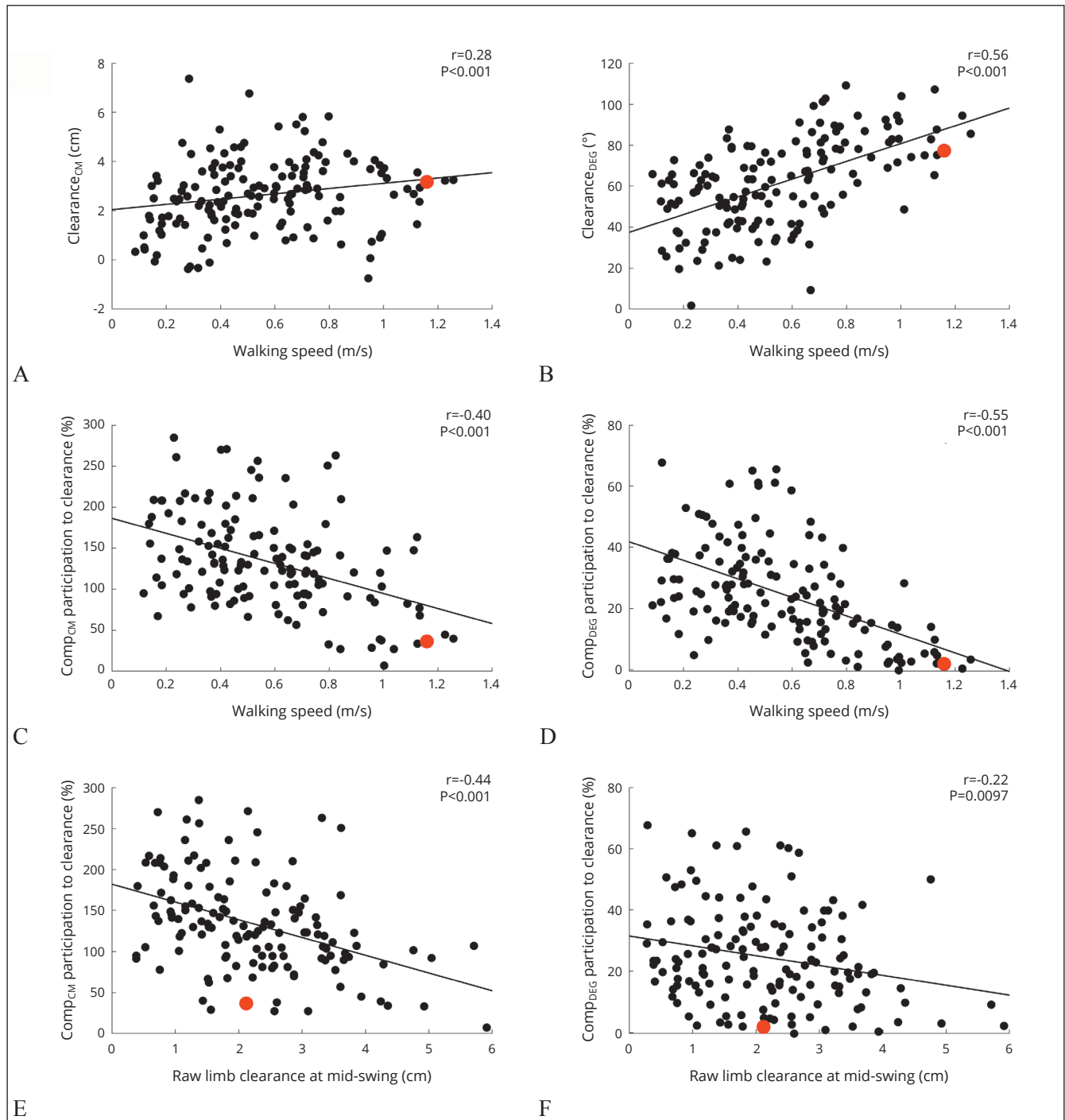


Figure 3.—Spearman's correlation between walking speed, toe clearance and kinematic outcomes. Black dots represent the post-stroke participants and the red dots are the median of the healthy control participants. Panels A, C, and E relate to the centimetric method of limb clearance description. Panels B, D and F relate to the angular method of limb clearance description. Walking speed is correlated to the centimetric limb clearance (Clearance_{CM}) in A, to the angular global limb clearance (Clearance_{DEG}) in B, to the participation of Comp_{CM} to Clearance_{CM} (expressed in percentage) in C and to the participation of Comp_{DEG} to Clearance_{DEG} (expressed in percentage) in D. Toe clearance at mid-swing is correlated to the participation of Comp_{CM} to Clearance_{CM} (expressed in percentage) in E and to the participation of Comp_{DEG} to Clearance_{DEG} (expressed in percentage) in F. Spearman's correlation coefficient r appears on each graph with its P value (significant if <0.004).

Correlations between walking speed and kinematic outcomes

Correlations between walking speed, raw limb clearance and kinematic outcomes are illustrated in Figure 3. Walking speed was weakly correlated to Clearance_{CM} (Figure 3A) and moderately correlated with Clearance_{DEG} (Figure 3B). The %Comp_{CM} and %Comp_{DEG} participation to the clearance were both moderately and negatively correlated with walking speed (Figure 3C, D). The %Comp_{CM} and %Comp_{DEG} were moderately and weakly correlated respectively to the raw limb clearance at mid-swing (Figure 3E, F).

Other correlations between the kinematic outcomes, walking speed and raw limb clearance were explored in Supplementary Digital Material 6 (Supplementary Figure 3).

Measurement bias between Clearance_{CM} and raw limb clearance

The mean difference between Clearance_{CM} and raw limb clearance was found to be -0.15 cm (P=0.016, 95% CI -2.64 to 2.33) in favor of raw limb clearance compared to Clearance_{CM} (Supplementary Digital Material 7: Supplementary Figure 4).

Discussion

The potential of ToulGaitViz has been presented in this study. It allows for a quantitative and comprehensive graphical way of describing global limb clearance and its shortening and compensation components. The significance of each component of ToulGaitViz is discussed hereafter.

Part A of ToulGaitViz report: limb clearance at mid-swing

The quantification of limb clearance at mid-swing (Figure 1A) is graphically represented by bar graphs in centimeters and in degrees. It shows the details of clearance, positive or negative, the shortening and compensation index and each segment or joint. A change in the size of a bar is easily seen between two 3DGAs and allows the identification of the segment or joint at the origin of the change. This quantification has been applied to 3DGAs made by one examiner in a standardized way in a cohort of 151 post-stroke participants undergoing routine care in a department specializing in Neuro-Orthopedics.

Participation of compensation to achieve clearance

Mean data shows that post-stroke participants achieve clearance with more compensations than healthy control

participants. The participation in percentage of compensation (%Comp) within clearance highlights the importance of compensations to achieve clearance. Indeed, the contribution of compensation is higher in post-stroke participants than in healthy control participants: 130% versus 33% (P<0.001) and 23% versus 1.4% (P<0.001) with centimetric and angular methods respectively. In 2018, Pongpipatpaiboon did not express the contribution of compensation to limb clearance in percentage terms but the authors showed that clearance was achieved in post-stroke participants for 3.3 cm of compensatory movement and 0.2 cm of limb shortening movement, *i.e.*, by 94.3% of compensatory movement.¹⁶ In the post-stroke population, participation of compensation is over 100% because the centimetric shortening index is negative and therefore to achieve clearance the amount of the centimetric compensation index is greater than the clearance index. The negative shortening index refers to the difficulty of post-stroke subjects to shorten their limbs. Little in 2014 and Haruyama in 2021 showed that with max hip-toe distance and the pelvic-toe distance respectively, shortening was about 1% of the leg length during the swing phase.^{12, 13} As the centimetric clearance in this study is measured at mid-swing and not at maximum limb shortening, we expected to observe a limb shortening of around 100% or more (*i.e.*, a negative centimetric shortening index).

In 2021, Haruyama quantified clearance with an angular method when the pelvis-toe distance was minimal during swing.¹² The sagittal clearance peak was 65.9° in post-stroke participants and 84.9° in healthy control participants whereas the frontal clearance peak was 10.6° and 1.4° respectively. Even though the computation method is not the same, our data support these previous results. Hence, some participants within the post-stroke population have a negative shortening index and therefore have to apply compensation strategies to overcome negative shortening (lengthening) of the limb. In this case, ToulGaitViz highlights the importance of the lack of limb shortening in post-stroke participants and the importance of compensatory movements, allowing us to compare both.

Non-proportionality of clearance between centimetric and angular methods

ToulGaitViz provides two ways of computing limb clearance (centimetric and angular methods). The present results highlight the fact that the angular method overestimated the sagittal contribution of hip, knee and ankle flexion relative to pelvic compensations and lower limb abduction. For example, a clearance of 2 degrees of pel-

vic obliquity brings about 1 cm of clearance while 10° of knee flexion also brings about 1 cm of clearance. Consequently, although commonly used in clinical practice, this angular method is likely to mask the importance of considering the compensations and their implication in the energy cost of walking.¹² The centimetric method (Clearance_{CM}) better highlights the importance of compensations in paretic limb clearance because it considers the real contribution of each segment to the shortening movements.

Relation between clearance index and walking speed

Walking speed and raw limb clearance are key factors for correlating kinematic outcomes. Indeed, comfortable walking speed is a good reflection of the functional abilities of post-stroke subjects²⁸ and is a determinant of gait kinematics.^{11, 29} Furthermore, raw limb clearance is directly influenced by lower limb shortening and compensatory movements.³⁰

The present results support the hypothesis that joint kinematics are dependent on walking speed because walking speed was moderately positively correlated to the limb clearance computed by the angular method¹¹ whereas it was weakly correlated to the limb clearance computed by the centimetric method. Increased walking speed induces increased limb flexion but does not increase limb clearance (Figure 3A, B). The contribution of compensations to limb clearance (%CompCM and %CompDEG) was moderately negatively correlated to walking speed (Figure 3C, D) which is in line with the hypothesis that compensatory movements require greater effort and therefore greater energy expenditure to achieve gait.³¹ Raw limb clearance default was moderately and weakly correlated to the participation of compensation to centimetric and angular clearance respectively. The participation of compensation seems to better reflect raw limb clearance default when it is measured by the centimetric method than by the angular method (Figure 3E, F).

Physiological clearance index from healthy control participants

The data of 48 healthy control participants can be used as physiological data for the definition of limb clearance, shortening and compensation as well as participation of shortening and compensation to limb clearance. Healthy control participants achieved an angular clearance of 78° from 77° of shortening and 1° of compensation with a respective participation of 98.6% and 1.4%. This result confirms that healthy control participants have almost

no compensation. However, centimetric clearance being equal to 3 cm is achieved by 2 cm of shortening and 1 cm of compensation with respective participations to clearance of 67% and 33%. This result shows that even though frontal angular clearance is very low, part of the physiological clearance of the limb is physiologically allowed by pelvic movement and discrete limb abduction. These pelvic movements and discrete limb abduction cannot be considered as compensatory movements because they do not compensate for any lack of limb shortening but highlight that part of the physiological clearance is allowed by frontal movement of the limb and hip hiking.

Part B of ToulGaitViz tool report: description of limb clearance movements in comparison to a participant-adjusted norm

Each movement of limb clearance is graphically compared to the norm on the graph in part B of Figure 1 which is not usual practice in clinical research where studies compare the effect of an intervention from angular raw data.^{16, 32-34} The definition of the norm in sagittal plane was participant-adjusted according to speed, body mass index, age and gender and other information was defined from the laboratory norms. The graphical report allows the clinician to see the segment or the joint that is the source of the clearance default on part A.

Understanding the origin of the shortening default allows us to discuss the most relevant therapeutic interventions (orthoses, botulinum toxin, surgery).^{6, 35}

Usability of ToulGaitViz in clinical and research practice

Individual clinical considerations

The cohort analysis (Supplementary Figure 2) shows that there is an important inter-individual variability. ToulGaitViz is useful for bringing a detailed and global analysis of one subject. Firstly, it identifies if there is a shortening default and an overuse of compensation. Secondly, the repartition of clearance between segments or joints and its comparison to the healthy control population allows us to make an initial definition of the origin of abnormalities. The description of the ten movements of limb clearance in comparison to the norm enables identification of the default movements or compensatory movements. This knowledge contributes towards global clinical consideration around a subject and his/her gait discomfort. ToulGaitViz is therefore a complement to clinical examinations, videos, kinetic and electromyography 3DGA reports.

Impact of an intervention on a population

Quantification enables the comparison of 3DGAs between subjects or before/after an intervention. The purpose of most of the neuro-orthopedic interventions after stroke is to reduce the shortening default. A few studies have shown that increased shortening by an intervention decreased compensation.¹⁶ ToulGaitViz allows the reproduction of such studies. It could be used to evaluate the impact of new or previous neuro-orthopedic interventions such as the real impact on compensation of an ankle-foot orthoses or the impact of a particular type of surgery. ToulGaitViz seems relevant for use in a standardized approach as proposed in the Clinical Movement Analysis Society standards³⁶ or Baker's guidelines.³⁷

It is hypothesized that the energy expenditure of gait is correlated to the movement of the center of mass and indirectly related to the quantity of compensation.^{38, 39} ToulGaitViz tool provides a quantity of compensation in centimeters and in degrees. Further research could focus on the correlation of gait energy expenditure and compensation.

When ToulGaitViz is performed several times over time, the use of a cane must be considered as it can have specific effects on the kinematic data. ToulGaitViz can also be used to evaluate the impact of the using a cane on the kinematic data.

Limitations of the study

The use of percentages to describe the contribution of compensation and shortening to limb clearance is a comprehensive way of comparing two subjects that do not have the same clearance. The limitation of this calculation is that when the clearance is very close to 0 cm or 0°, a numerical error can appear. In this case, the shortening or compensation percentage may be superior to 100% and tend towards infinity so the contribution of compensation is not informative.

Normative data of the description of limb clearance movements in comparison to a participant-adjusted norm (part B of Figure 1) are participant-adjusted according to regressors for the sagittal plane biomarkers of hip, knee and ankle. Norms for other kinematic data were not adjusted to walking speed due to a lack of data in the literature. In the future, if norms adjusted to walking speed¹¹ are published for all kinematic data (including the pelvis and the frontal and horizontal planes for the lower limbs), they can be easily implemented in ToulGaitViz.

Raw limb clearance is the result of the clearance of the segments in centimeters. The Bland-Altman graph

(Supplementary Figure 4) shows that clearance estimation from segments in centimeters is very close to raw limb clearance with a large confidence interval. This may be due to the variability of the Plug-In Gait modeling.⁴⁰

Conclusions

ToulGaitViz is a new tool for quantifying and interpreting clearance of the lower limb. It should be used in clinical practice to improve understanding of this clearance and to guide neuro-orthopedic treatments. This tool could allow further studies to focus on the understanding of gait modification after a treatment and to clarify the link between gait energy cost as well as subjects' needs on the one hand and the level of compensatory movements during gait on the other hand. ToulGaitViz encourages the use of 3DGA by all and may improve the relevance of kinematics data interpretation.

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Conflicts of interest

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Authors' contributions

Emmeline Montané: conceptualization; data analysis; software development; writing - original draft. Camille Cormier: data interpretation; writing - review and editing. Marino Scandella: data collection; writing - review and editing. Adrian Cangelosi: data analysis; data interpretation; writing - review and editing. Philippe Marque: data interpretation; writing - review and editing. Florent Moissenet: methodology; data analysis; writing - review and editing. David Gasq: conceptualization; project administration; methodology; software development; writing - original draft. All authors read and approved the final version of the manuscript.

History

Article first published online: October 23, 2023. - Manuscript accepted: October 4, 2023. - Manuscript revised: September 4, 2023. - Manuscript received: March 20, 2023.

Supplementary data

For supplementary materials, please see the HTML version of this article at www.minervamedica.it