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(54) **GAIT ANALYSIS SYSTEM**

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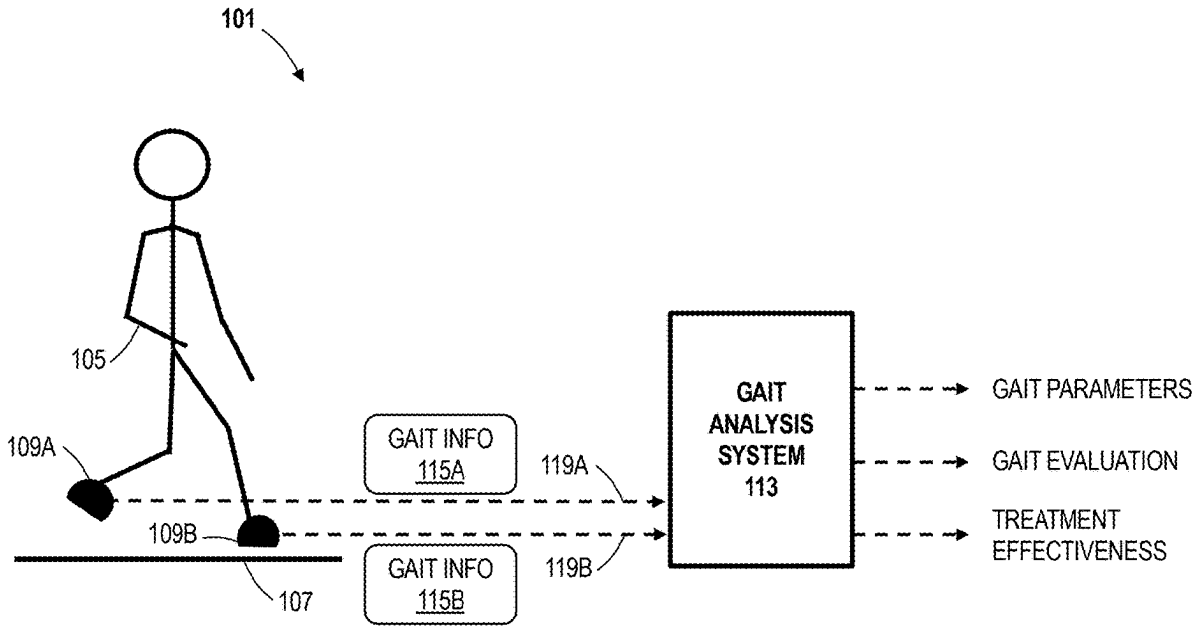
(57) **ABSTRACT**

A gait analysis system is disclosed. Some implementations of the gait analysis system include instrumented footwear including mobile sensors, a processor, a computer-readable data storage device storing program instructions. The program instructions can control the system to perform operations, including, determining gait information of a user performing a test routine, using the instrumented footwear. The operations can also include determining gait parameters based on the gait information. The operations can also include determining gait symmetry of the user based on the gait parameters. The operations can also include determining a gait signature of the user based on the gait parameters. The operations can also include determining a treatment effect based on the gait signature.



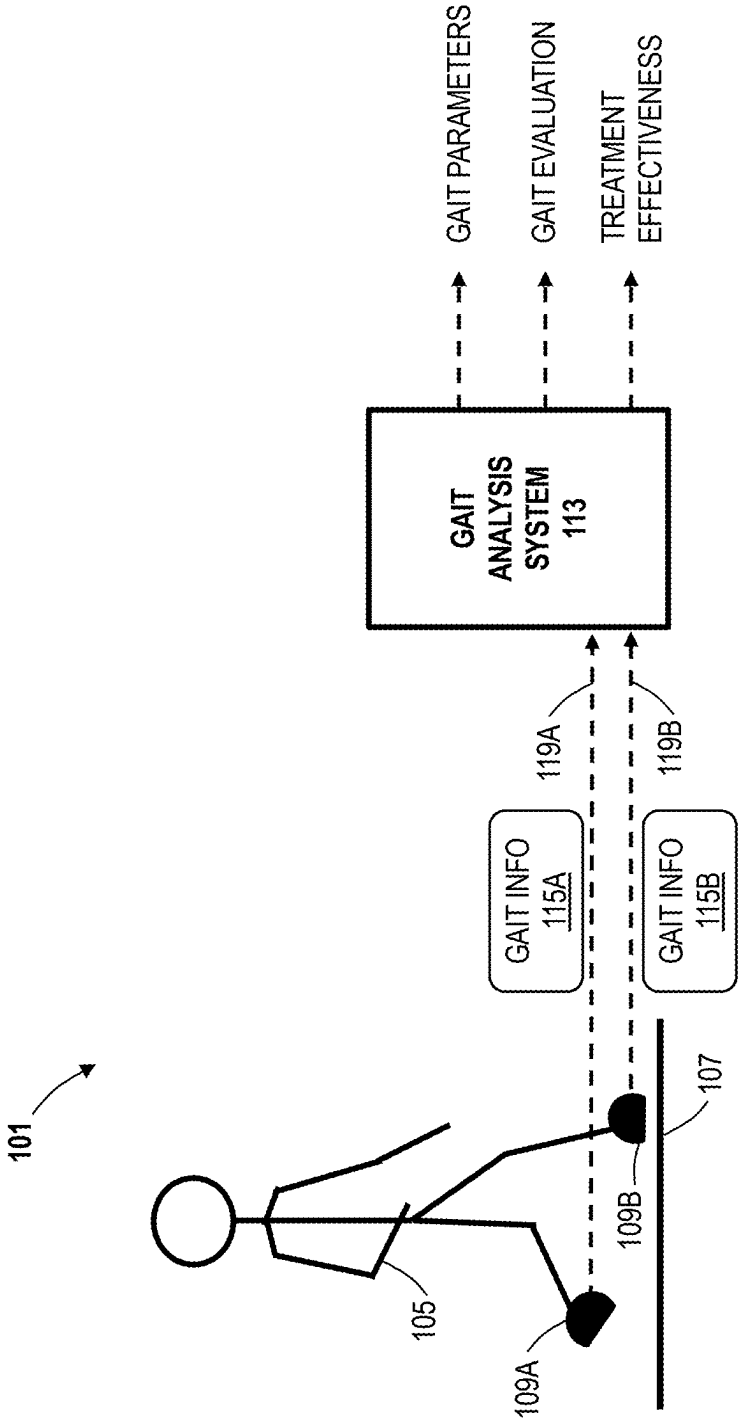

GAIT PARAMETERS
GAIT EVALUATION
TREATMENT EFFECTIVENESS
GAIT ANALYSIS SYSTEM 113
119A
119B
GAIT INFO 115A
GAIT INFO 115B
101
105
107
109A
109B

FIG. 1A

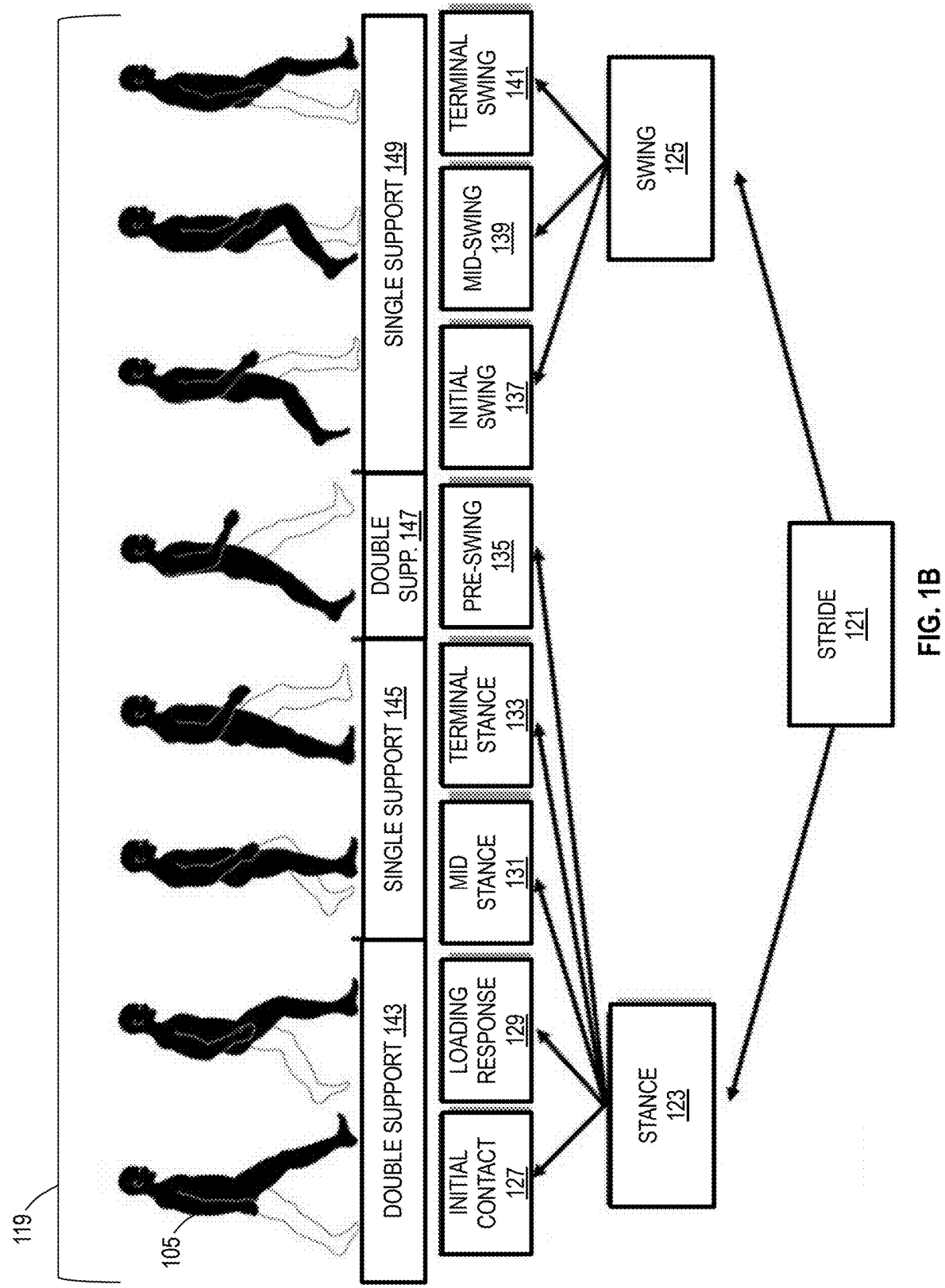

119
105
DOUBLE SUPPORT 143
SINGLE SUPPORT 145
DOUBLE SUPP. 147
SINGLE SUPPORT 149
INITIAL CONTACT 127
LOADING RESPONSE 129
MID STANCE 131
TERMINAL STANCE 133
PRE-SWING 135
INITIAL SWING 137
MID-SWING 139
TERMINAL SWING 141
STANCE 123
SWING 125
STRIDE 121

FIG. 1B

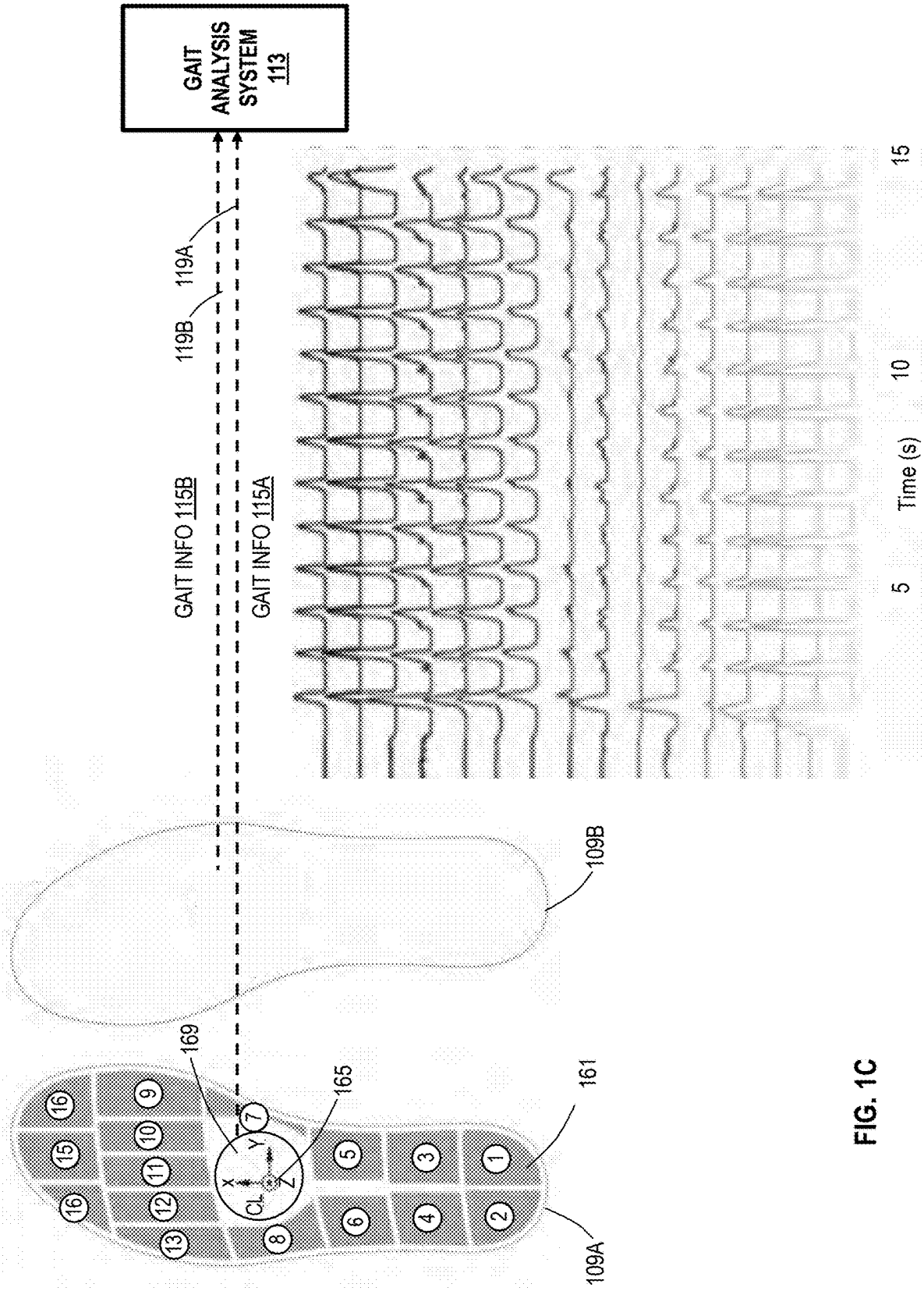

GAIT ANALYSIS SYSTEM 113
119A
119B
GAIT INFO 115B
GAIT INFO 115A
5
10
15
Time (s)
109B
109A
161
165
169
CL
X
Y
Z
1
2
3
4
5
6
7
8
9
10
11
12
13
15
16

FIG. 1C

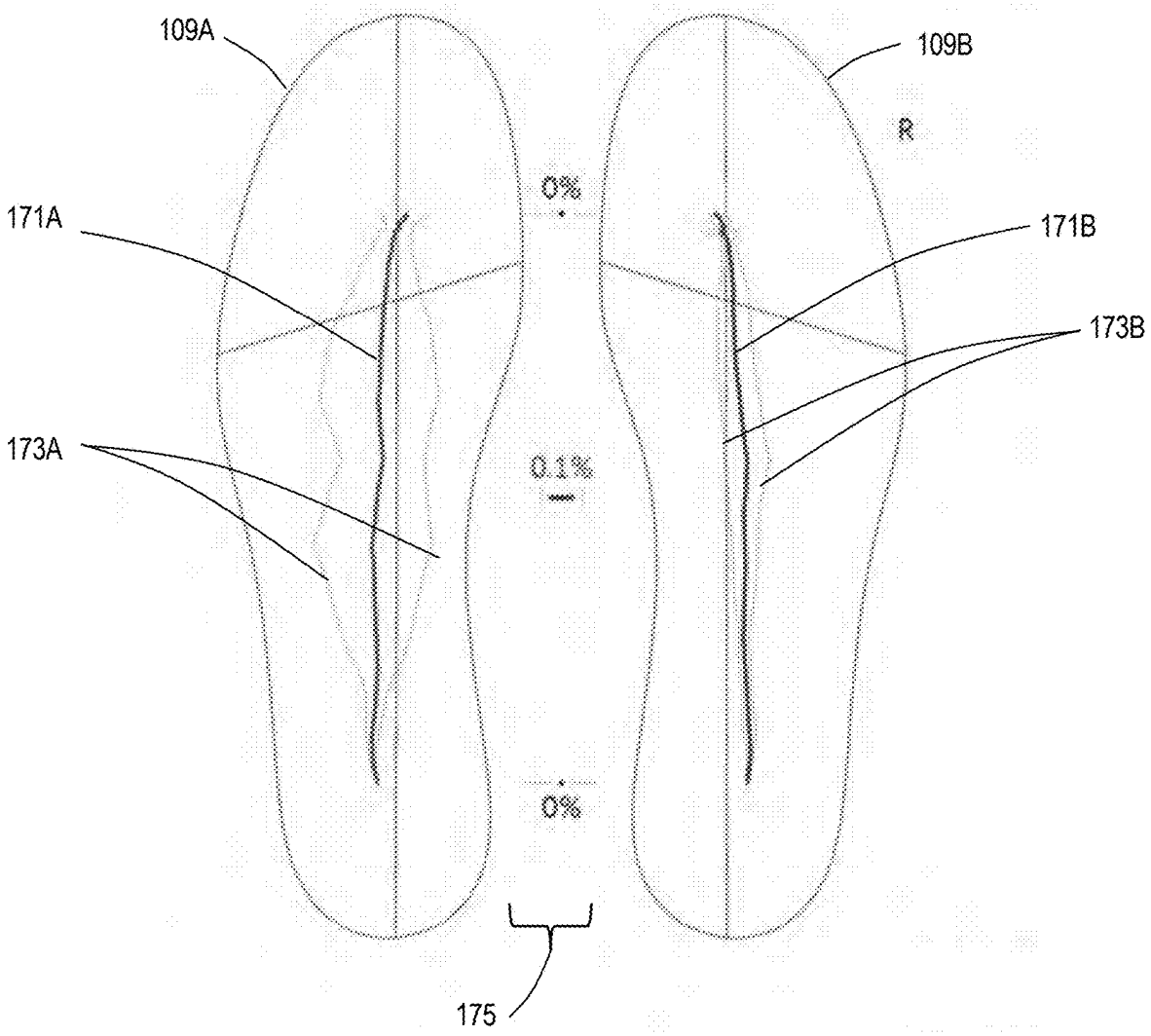


FIG. 1D

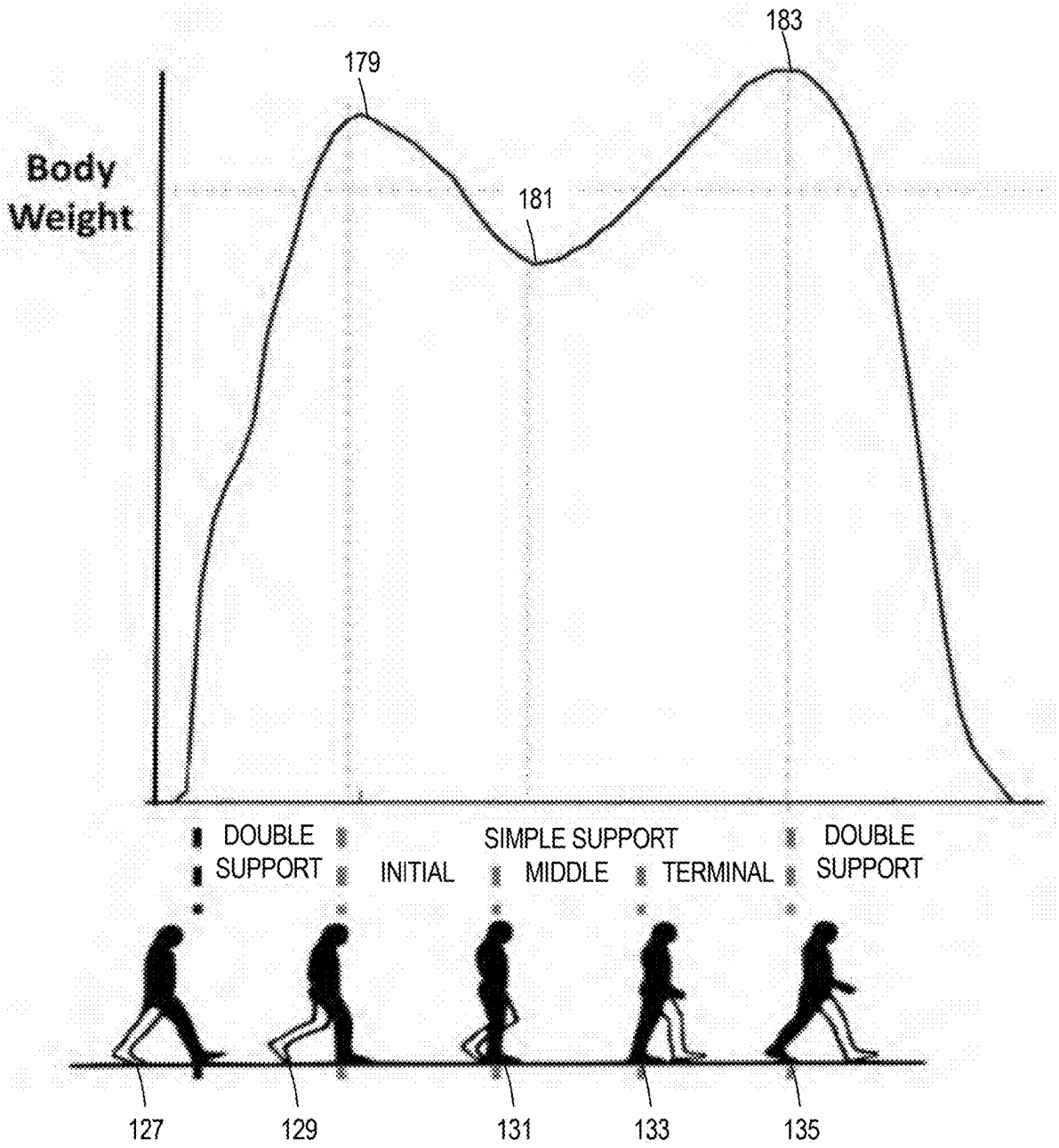

Body Weight
179
181
183
DOUBLE SUPPORT
INITIAL
SIMPLE SUPPORT
MIDDLE
TERMINAL
DOUBLE SUPPORT
127
129
131
133
135

FIG. 1E

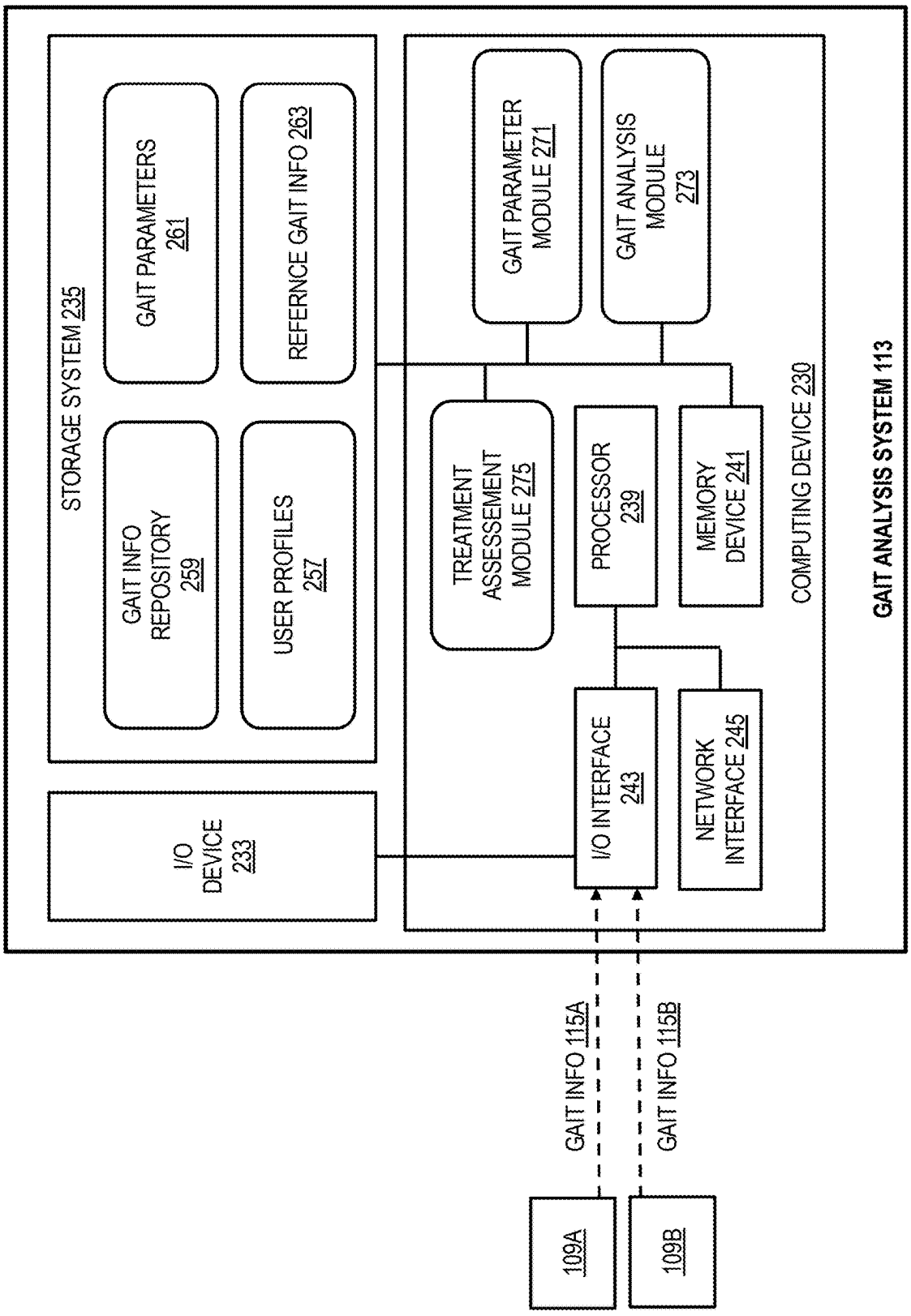

GAIT ANALYSIS SYSTEM 113
STORAGE SYSTEM 235
GAIT INFO REPOSITORY 259
GAIT PARAMETERS 261
USER PROFILES 257
REFERNCE GAIT INFO 263
I/O DEVICE 233
COMPUTING DEVICE 230
GAIT PARAMETER MODULE 271
GAIT ANALYSIS MODULE 273
TREATMENT ASSESSEMENT MODULE 275
PROCESSOR 239
MEMORY DEVICE 241
I/O INTERFACE 243
NETWORK INTERFACE 245
GAIT INFO 115A
GAIT INFO 115B
109A
109B

FIG. 2

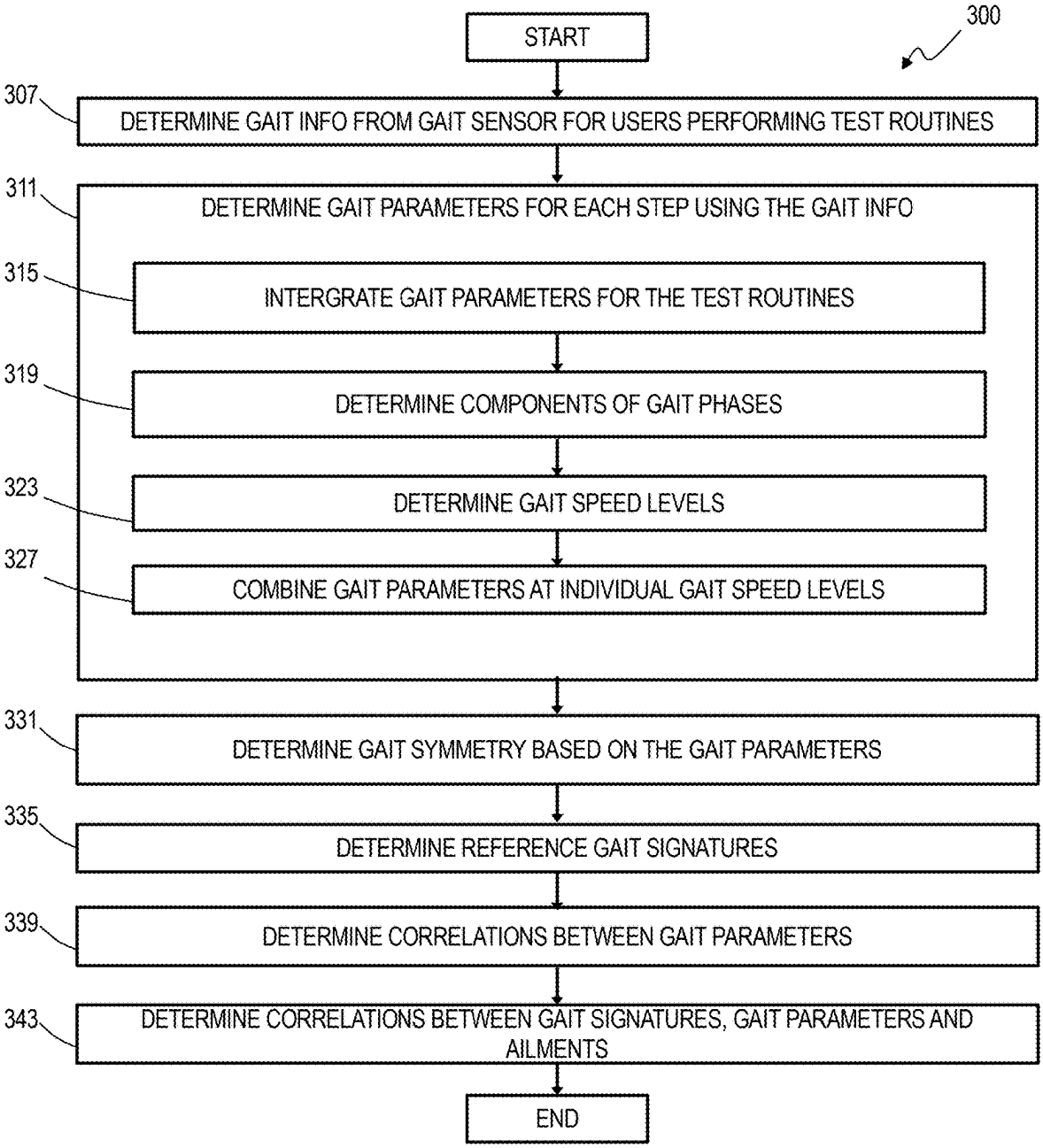

300
START
307
DETERMINE GAIT INFO FROM GAIT SENSOR FOR USERS PERFORMING TEST ROUTINES
311
DETERMINE GAIT PARAMETERS FOR EACH STEP USING THE GAIT INFO
315
INTERGRATE GAIT PARAMETERS FOR THE TEST ROUTINES
319
DETERMINE COMPONENTS OF GAIT PHASES
323
DETERMINE GAIT SPEED LEVELS
327
COMBINE GAIT PARAMETERS AT INDIVIDUAL GAIT SPEED LEVELS
331
DETERMINE GAIT SYMMETRY BASED ON THE GAIT PARAMETERS
335
DETERMINE REFERENCE GAIT SIGNATURES
339
DETERMINE CORRELATIONS BETWEEN GAIT PARAMETERS
343
DETERMINE CORRELATIONS BETWEEN GAIT SIGNATURES, GAIT PARAMETERS AND AILMENTS
END

FIG. 3

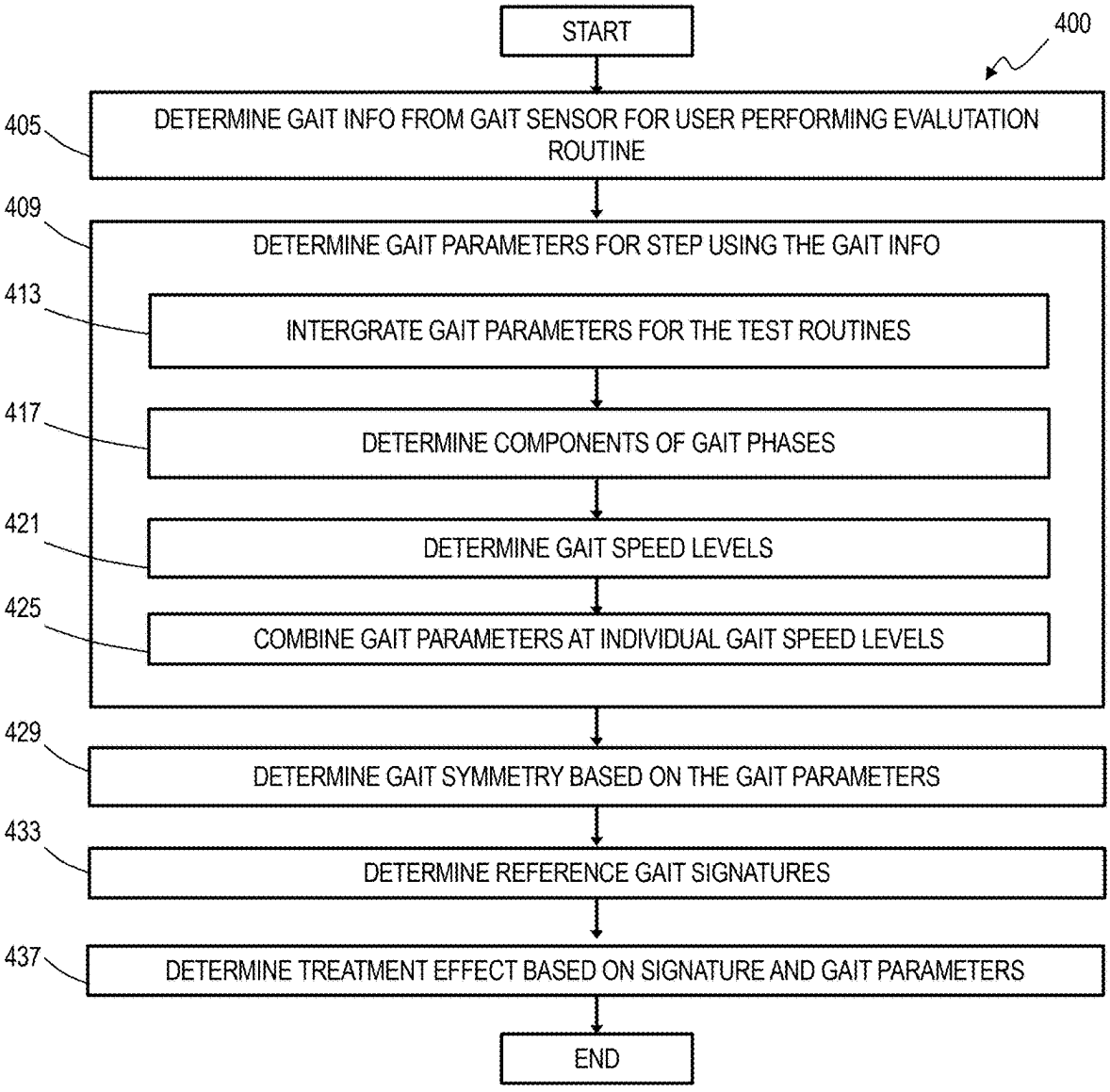

START
400
405
DETERMINE GAIT INFO FROM GAIT SENSOR FOR USER PERFORMING EVALUTATION ROUTINE
409
DETERMINE GAIT PARAMETERS FOR STEP USING THE GAIT INFO
413
INTERGRATE GAIT PARAMETERS FOR THE TEST ROUTINES
417
DETERMINE COMPONENTS OF GAIT PHASES
421
DETERMINE GAIT SPEED LEVELS
425
COMBINE GAIT PARAMETERS AT INDIVIDUAL GAIT SPEED LEVELS
429
DETERMINE GAIT SYMMETRY BASED ON THE GAIT PARAMETERS
433
DETERMINE REFERENCE GAIT SIGNATURES
437
DETERMINE TREATMENT EFFECT BASED ON SIGNATURE AND GAIT PARAMETERS
END

FIG. 4

Center of Pressure (COP)		
Mean gait line length (left)	mm	Length of the average gait line (left foot)
Mean gait line length (right)	mm	Length of the average gait line (right foot)
Mean gait line width (left)	mm	Width of the average gait line (left foot)
Mean gait line width (right)	mm	Width of the average gait line (right foot)
Mean COP (AP/ML) in x direction (left)	mm	Mean of center of pressure in x direction (left foot)
Mean COP (AP/ML) in y direction (left)	mm	Mean of center of pressure in y direction (left foot)
Mean COP (AP/ML) in x direction (right)	mm	Mean of center of pressure in x direction (right foot)
Mean COP (AP/ML) in y direction (right)	mm	Mean of center of pressure in y direction (right foot)
SD COP (AP/ML) in x direction (left)	mm	Standard deviation of center of pressure in x direction (left foot)
SD COP (AP/ML) in y direction (left)	mm	Standard deviation of center of pressure in y direction (left foot)
SD COP (AP/ML) in x direction (right)	mm	Standard deviation of center of pressure in x direction (right foot)
SD COP (AP/ML) in y direction (right)	mm	Standard deviation of center of pressure in y direction (right foot)
Length of Bounding box of COP (AP/ML)(left)	mm	Length of the box just containing all COP points (left foot)
Width of Bounding box of COP (AP/ML)(left)	mm	Width of the box just containing all COP points (left foot)
Length of Bounding box of COP (AP/ML)(right)	mm	Length of the box just containing all COP points (right foot)
Width of Bounding box of COP (AP/ML)(right)	mm	Width of the box just containing all COP points (right foot)
Mean COP velocity (left)	mm/s	Mean velocity of the COP travelling across the sensor insole surface (left foot)
Mean COP velocity (right)	mm/s	Mean velocity of the COP travelling across the sensor insole surface (right foot)
COP trace length (left)	mm	Overall travel of the COP across the sensor insole surface (left foot)
COP trace length (right)	mm	Overall travel of the COP across the sensor insole surface (right foot)

FIG. 5A

Ground Reaction Force (GRF)		
Mean total force during stance phase (left)	N	Mean force of all steps (left foot)
Mean total force during stance phase (right)	N	Mean force of all steps (right foot)
Maximum total force during stance phase (left)	N	Maximum force of all steps (left foot)
Maximum total force during stance phase (right)	N	Maximum force of all steps (right foot)
Mean of all maxima of total force during all stance phase (left)	N	Averages of maximum total force of all steps (left foot)
Mean of all maxima of total force during all stance phase (right)	N	Averages of maximum total force of all steps (right foot)
Temporal parameters		
Mean gait cycle time	s	Time from the one help strike to the next heel strike of the same foot, averaged over all steps
Mean gait cadence	Strides/min	Number of strides per minute
Mean double support time	s	Mean double support time, relative to the mean gait cycle time
Mean fraction of double support	%	Mean double support time, relative to the mean gait cycle time
Mean double support time (left)	s	Side-specific double support time(left), with the left mean double support time considering the time starting from the right foot's heel strike to the left foot's toe off (and vice versa)
Mean double support time (right)	s	Side-specific double support time(right), with the right mean double support time considering the time starting from the left foot's heel strike to the right foot's toe off (and vice versa)
Mean step duration (left)	s	Average time between consecutive heel strike of the left foot
Mean step duration (right)	s	Average time between consecutive heel strike of the right foot
Mean stance duration (left)	s	Time from heel strike to toe off (of left foot side), averaged over all steps
Mean stance duration (right)	s	Time from heel strike to toe off (of right foot side), averaged over all steps

FIG. 5B

Temporal parameters		
SD stance duration (left)	s	Standard deviation of duration of stance phase (left foot)
SD stance duration (right)	s	Standard deviation of duration of stance phase (right foot)
Mean swing duration (left)	s	Time from toe off to heel strike (of left foot side), averaged over all steps
Mean swing duration (right)	s	Time from toe off to heel strike (of right foot side), averaged over all steps
SD swing duration (left)	s	Standard deviation of duration of swing phase (left foot)
SD swing duration (right)	s	Standard deviation of duration of swing phase (right foot)
Mean fraction of stance phase (left)	%	Mean stance duration, relative to the mean gait cycle time (left foot)
Mean fraction of stance phase (right)	%	Mean stance duration, relative to the mean gait cycle time (right foot)
SD fraction of stance phase (left)	%	Standard deviation of fraction of stance phase (left foot)
SD fraction of stance phase (right)	%	Standard deviation of fraction of stance phase (right foot)
Mean fraction of swing duration (left)	%	Mean swing duration, relative to the mean gait cycle time (left foot)
Mean fraction of swing duration (right)	%	Mean swing duration, relative to the mean gait cycle time (right foot)
SD fraction of swing duration (left)	%	Standard deviation of fraction of swing phase (left foot)
SD fraction of swing duration (right)	%	Standard deviation of fraction of swing phase (right foot)
Force raise (left)	s	Time to first force peak after initial ground contact (left foot)
Force raise (right)	s	Time to first force peak after initial ground contact (right foot)
Takeoff Dynamics (left)	1	Ratio of force value of force minimum in stance phase and 2nd force peak (takeoff) (left foot)
Takeoff Dynamics (right)	1	Ratio of force value of force minimum in stance phase and 2nd force peak (takeoff) (right foot)
Gait direction dynamics (left)	g	Amplitude of foot acceleration in direction of walking (left foot)
Gait direction dynamics (right)	g	Amplitude of foot acceleration in direction of walking (right foot)
Spatial parameters		
Mean stride length	m	The displacement of the same foot in walking direction. This parameter is the mean over all detected steps. The mean is determined from left and right data, separately, and finally averaged over left and right
Foot flexibility (left)	g	Amplitude of foot acceleration in body's vertical direction (left foot)
Foot flexibility (right)	g	Amplitude of foot acceleration in body's vertical direction (right foot)
Walking distance	m	The walking distance traveled over the entire measurement
Mean walking speed	m/s	The mean stride length divided by the mean gait cycle time.

FIG. 5C

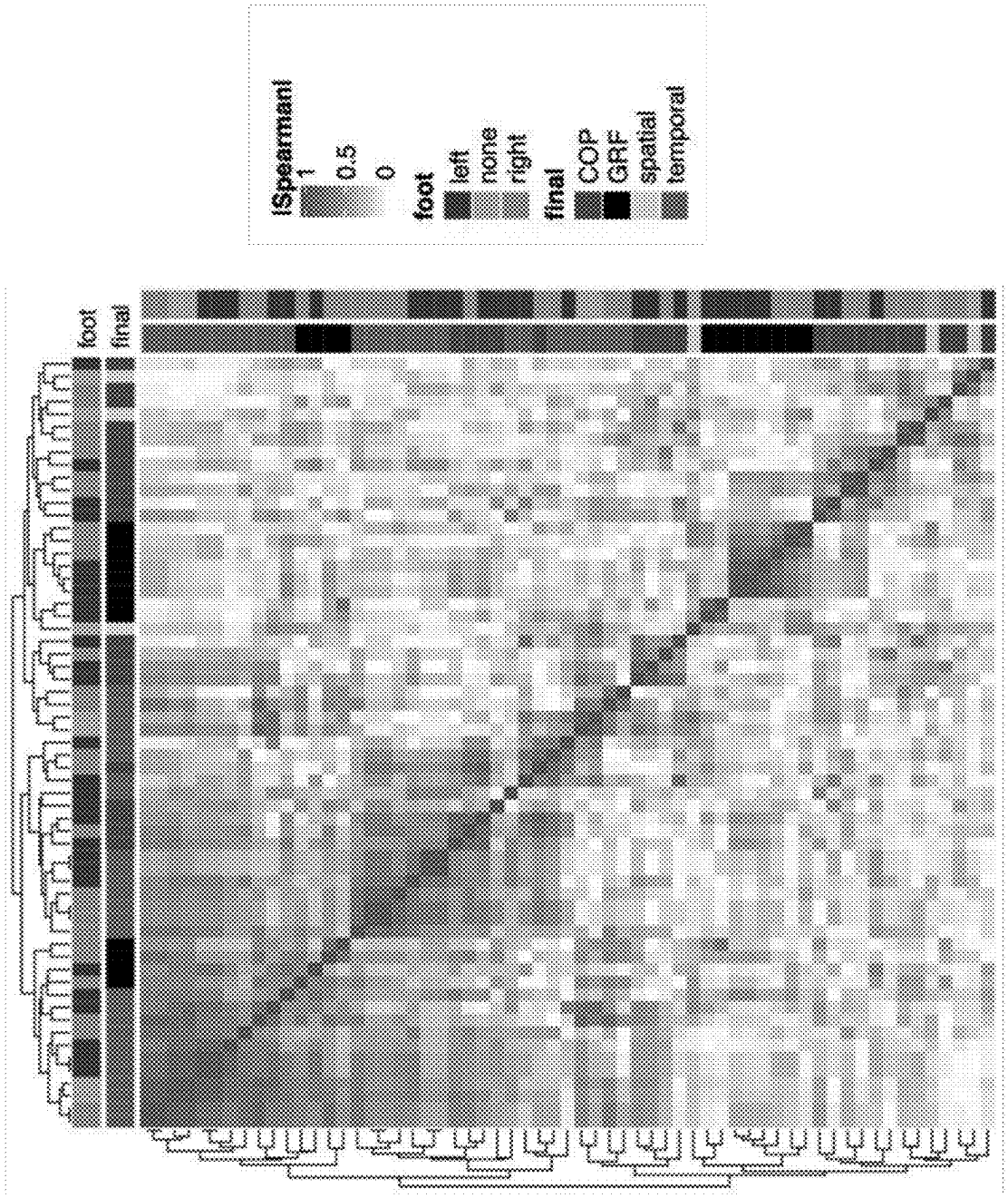

|Spearman|
1
0.5
0
foot
left
none
right
final
COP
GRF
spatial
temporal
foot
final

FIG. 6A

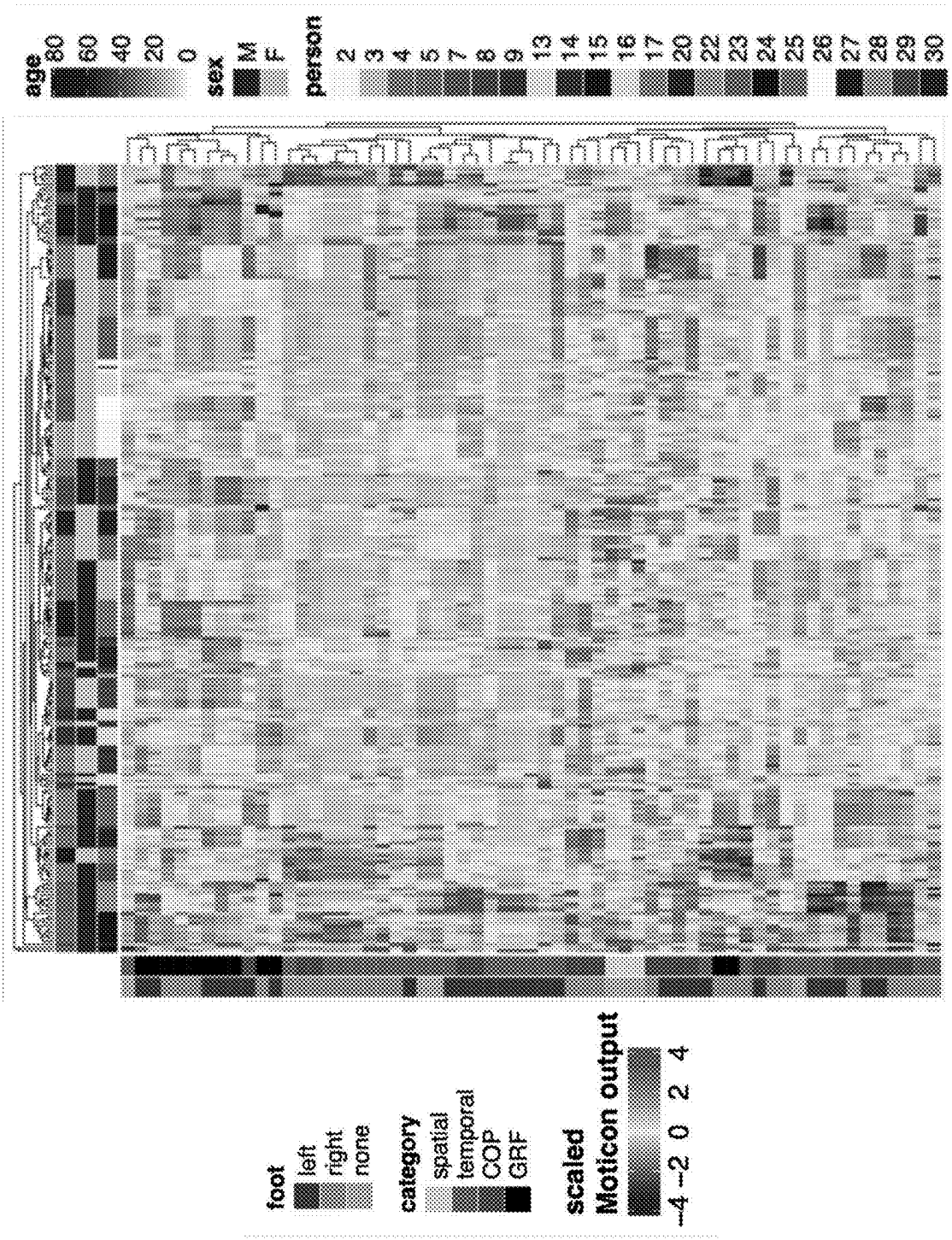

age
80
60
40
20
0
sex
M
F
person
2
3
4
5
7
8
9
13
14
15
16
17
20
22
23
24
25
26
27
28
29
30
foot
left
right
none
category
spatial
temporal
COP
GRF
scaled
Moticon output
−4
−2
0
2
4

FIG. 6B

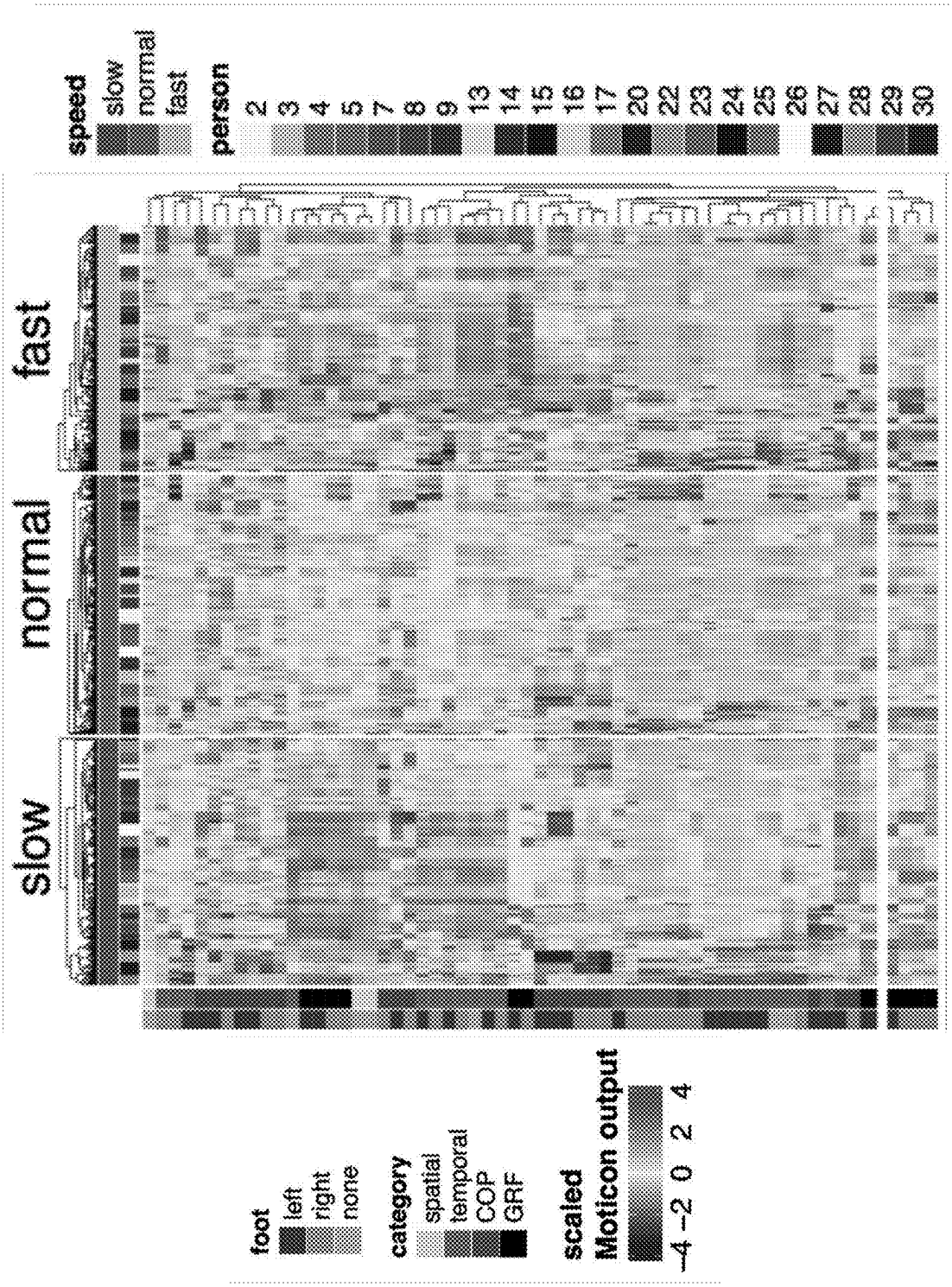

speed
slow
normal
fast
person
2 3 4 5 7 8 9 13 14 15 16 17 20 22 23 24 25 26 27 28 29 30
slow
normal
fast
foot
left
right
none
category
spatial
temporal
COP
GRF
scaled
Moticon output
−4 −2 0 2 4

FIG. 6C

GAIT ANALYSIS SYSTEM

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application is a continuation of and claims the benefit of priority to U.S. application Ser. No. 17/326,619, filed May 21, 2021, which claims priority to U.S. Provisional Application No. 63/030,006, filed May 26, 2020, and U.S. Provisional Application No. 63/054,007, filed Jul. 20, 2020, the contents of each of which are incorporated herein by reference in their entireties.

BACKGROUND

[0002] Gait disorders can result from a wide variety of injuries, diseases, and other ailments. Currently, tests used to diagnose gait disorders often involve simple functional assessments. However, data collected from such tests is subjective and does not provide sufficient information to assess the relative severity of afflictions. In some cases, a clinical laboratory may perform gait evaluations. However, the high cost and complexity of laboratory-grade sensors systems may limit their size. As such, they may not allow evaluation of gaits over a substantial distance.

SUMMARY

[0003] The following presents a simplified summary of the disclosed subject matter in order to provide a basic understanding of some aspects of the disclosed subject matter. This summary is not intended to identify key or critical elements of the disclosed subject matter or delineate the scope of the claimed subject matter.

[0004] The present disclosure provides gait analysis systems and methods. In some implementations, a gait analysis system includes instrumented footwear including one or more mobile sensors, a processor, a computer-readable data storage device storing program instructions. The program instructions, when executed by the processor, can control the system to perform operations, including, determining, using the instrumented footwear, gait information of a user performing a test routine. The operations can also include determining gait parameters based on the gait information. The operations can also include determining gait symmetry of the user based on the gait parameters. The operations can also include determining a gait signature of the user based on the gait parameters. The operations can also include determining a treatment effect based on the gait signature.

DRAWINGS

[0005] FIG. **1**A shows a block diagram illustrating an exemplary environment for implementing systems and methods in accordance with aspects of the present disclosure.

[0006] FIG. **1**B shows elements of a stride determined by systems and methods in accordance with aspects of the present disclosure.

[0007] FIG. **1**C shows gait information provided by instrumented footwear to a gait analysis system in accordance with aspects of the present disclosure.

[0008] FIG. **1**D shows gait parameters in relation to instrumented footwear in accordance with aspects of the present disclosure.

[0009] FIG. **1**E shows gait parameters in relation to gait phases in accordance with aspects of the present disclosure.

[0010] FIG. **2** shows a block diagram illustrating an example of a gait analysis system in accordance with aspects of the present disclosure.

[0011] FIG. **3** shows a flow block diagram illustrating an example of a method for determining reference gait information in accordance with aspects of the present disclosure.

[0012] FIG. **4** shows a flow block diagram illustrating an example of a method for evaluating effectiveness of treatments in accordance with aspects of the present disclosure.

[0013] FIGS. **5**A, **5**B, and **5**C show gait parameters in accordance with aspects of the present disclosure.

[0014] FIGS. **6**A, **6**B, and **6**C show heat maps illustrating correlations between gait parameters in accordance with aspects of the present disclosure.

DETAILED DESCRIPTION

[0015] The present disclosure relates to gait evaluation. More specifically, the present disclosure relates to evaluating gaits and determining treatment effects based on the gait evaluations. Treatment effects are relative improvements in an individual's gait resulting from treatment of an affliction in comparison to a reference gait. Implementations of systems and methods disclosed herein generate gait information over a several strides using wearable sensors, determine gait parameters based on the gait information, determine gait signatures based on the gait parameters, and determine effectiveness of treatments based on the gait signatures and gait parameters.

[0016] Reference will now be made to specific implementations illustrated in the accompanying drawings. In the following detailed description, numerous specific details are set forth to provide a thorough understanding of the disclosed implementations. However, it will be apparent to one of ordinary skill in the art that implementations may be practiced without these specific details. In other instances, well-known methods, procedures, components, circuits, and networks have not been described in detail so as not to unnecessarily obscure aspects of the implementations.

[0017] FIG. **1**A shows a system block diagram illustrating an example environment **101** for implementing systems and methods in accordance with aspects of the present disclosure. The environment IOI includes a user **105** traversing the ground **107** on foot while wearing instrumented footwear **109**A and **109**B. The instrumented footwear **109**A and **109**B generates respective gait information **115**A and **115**B and provides it to the gait analysis system **113** using one or more communication links **119**A and **119**B. For example, the gait analysis system **113** can receive the gait information **115**A, **115**B from the instrumented footwear **109**A, **109**B while the user **105** performs a test routine involving walking, running, and standing.

[0018] The user **105** can be any individual. In some implementations, the user **105** can be an individual having an affliction that affects the individual's **105** gait for which the user **105** may be receiving treatment, such as physical therapy. The afflictions can be, for example, damage, deterioration, or malformation of the individual's **105** musculoskeletal or neurological systems that cause asymmetries in the user's **105** stride. For example, nerve damage from a herniated disk in the user's spine may cause the user **105** to favor one foot over the other. Additionally, in some implementations, the user **105** can be an unafflicted individual lacking or substantially lacking any gait-affecting ailments.

The user **105** can generate reference gait information **115**A, **115**B representing an unafflicted stride.

[0019] The instrumented footwear **109**A, **109**B can be a pair of instrumented shoes, insoles, socks, or other foot covering wearable by the user **105**. The instrumented footwear **109**A, **109**B can comprise mobile sensors, including accelerometers, gyroscope, pressure sensors and force transducers. The instrumented footwear **109**A, **109**B can also include a processor, a computer-readable memory, and a data communication device. In some implementations, the processor, the computer-readable memory, and the data communication device are provided by an application-specific integrated circuit (ASIC) that amplifies, conditions, normalizes, and combines signals output by the sensors to generate gait information **115**A, **115**B, which the processor communicates to the gait analysis system **113** using the data communication device via the communication links **119**A, **119**B. In some implementations, the instrumented footwear **109**A, **109**B can be MOTICON SCIENCE INSOLES by MOTICON REGO AG, DE.

[0020] The gait analysis system **113** can be one or more computing devices that analyze the gait information **115** to determine gait parameters. Using the gait parameters, the gait analysis system **113** can evaluate the user's **105** gait. Additionally, based on the gait parameters and gait analysis, the gait analysis system **113** can determine the effectiveness of treatments the user **105** may be undergoing. For example, the gait analysis system **113** can compare the user's **105** current gait parameters to their past gait parameters and other reference information to identify improvements in performance.

[0021] The communication links **119**A, **119**B can be any wired links, wireless links, or combination thereof that use any combination of one or more types of transmission techniques and protocols. For example, the communication links **119**A and **119**B can use the BLUETOOTH® wireless communication protocol. In some implementations the instrumented footwear **109**A and **109**B can stream the information to the gait analysis system **113** via the communication links **119**A, **119**B. In some other implementations, the instrumented footwear **109**A and **109**B can bundle and transmit the gait information **115**A, **115**B via the communication links **119**A, **119**B after completion of a test routine.

[0022] FIG. **1**B shows elements of a stride **121** of the user **105** measurable over a distance **119** by systems and methods in accordance with aspects of the present disclosure. The stride **121** includes a stance phase **123** and a swing phase **125**. The components of the stance phase **123** can include an initial contact **127**, a loading response **129**, a mid-stance **131**, a terminal stance **133**, and a pre-swing **135**. The components of the swing phase **125** can include an initial swing **137**, a mid-swing **139**, and a terminal swing **141**. Further, the initial contact **127**, the loading response **129**, can be a first combination in which both of the user's **105** feet contact the ground, which is referred to as a double support movement **143**. The mid-stance **131** and the terminal stance **133** can be a second combination in which only one of the user's **105** feet contact the ground, which is referred to as single support movement **134**. The pre-swing **135** can be a second double support movement **147**. The initial swing **137**, the mid-swing **139**, and the terminal swing **141** can be a second single support movement **149**. While FIG. **1**B shows a single stride **121** over the distance **119**, it is understood that systems and methods consistent with those disclosed herein can involve gait evaluation routines including two or more strides over greater distances.

[0023] FIG. **1**C shows gait information **115**A, **115**B provided by the instrumented footwear **109**A or **109**B to the gait analysis system **113** through the communication link **119**A, **119**B in accordance with aspects of the present disclosure. In some implementations, the instrumented footwear **109**A, **109**B includes force sensors **116** and an accelerometer **165**. For example, the force sensors **161** can measure vertical pressure applied between the user's **105** foot and ground. Additionally, in some implementations, the force sensors **161** can be distributed on over the area of the instrumented footwear **109**A, **109**B. As illustrated in the example shown in FIG. **1**C, the instrumented footwear **109**A, **109**B can include **16** force sensors **161** substantially distributed over the entire surface area of the instrumented footwear **109**A, **109**B. In some implementations, the force sensors **161** are grouped at contact points corresponding to the balls and heel of the user's feet. In some implementations, the force sensors **161** are distributed over substantially over the entire area of the instrumented footwear **109**A, **109**B with increased density at the contact points corresponding to the balls and heel.

[0024] Additionally, the instrumented footwear **109**A, **109**B can include one or more accelerometers **165** that output data indicating acceleration in one or more axes. In some implementations, the accelerometer **165** is a multi-axis (vertical, X-axis), horizontal, Y-axis), and elevation, Z-axis) accelerometer that can measure acceleration in six degrees of freedom (forward translation (+X-axis), backward translation (−X-axis), right (+Y-axis), left (−Y-axis), up (+Z-axis), down (−Z-axis), pitch (rotation around X-axis), roll (rotation around Y-axis), and yaw (rotation around Z-axis). For example, the accelerometer **165** measurement unit can be a three-dimensional gyroscope.

[0025] Further, the footwear **109**A, **109**B can include controllers **169**, including respective microprocessors, data input/output (I/O) circuits, data conditioning circuits, and transmitters (not shown). In some implementations, the controllers **169** can also include the accelerometers **165**. The controllers **169** collect data from the force sensors **161** and accelerometers **165** via the digital 1/0 circuits at a rate between about 30 hertz and about 120 hertz. Additionally, the controllers **169** can include hardware, software, or a combination thereof that amplifies, conditions, and processes data from the force sensors **161** and accelerometers **165** to determine the gait information **115**A, **115**B. Further, the controller **169** can transmits the gait information **115**A, **115**B using the transmitter via the communication links **119**A, **119**B. While FIG. **1**C only illustrates gait information **115**A and elements of instrumented footwear **109**A, including force sensors **161**, accelerometer **165**, and controller **169**, it is understood the instrumented footwear **109**B can include the same or similar sensors producing substantially the same or similar gait information **115**B.

[0026] The gait information **115**A, **115**B can include, for example, information representing a total ground reaction force, which can be the sum of the outputs of the force sensors **161** multiplied by the respective surface area of the force sensors **161**. Additionally, the controller **169** can determine respective centers of pressure for the instrumented footwear **109**A, **109**B. Further, the controller **169** can determine respective heel strike (initial contact) and toe off (stance termination) events timepoint are determined

from total force, individual force, center of pressure and acceleration along anterior-posterior direction. Other data determined by the controller **169** can include, pressure applied on each pressure sensor, 3D acceleration, and 3D angular velocity.

[0027] FIG. 1D illustrates an example of gait lines **171**A and **171**B determined by the gait analysis system **113** based on the gait information **115**A and **115**B from the instrumented footwear **109**A and **109**B. A gait line represents the translational movement of the center of pressure (COP) during the stance phase (e.g. stance **123**) of a stride (e.g., stride **121**). The gait lines **171**A, **171**B represent the average gait line of steps taken during a test walk. Gait deviation lines **173**A and **173**B represent the standard deviation of the gait lines **171**A, **171**B in a media-lateral direction over the walk. The differences between the left and right foot are indicated by visual lines and percentage values **175**. The percentage values are with respect to the insole length and width. For example, FIG. 1D illustrates a 1% difference between the left and the right foot in a media-lateral direction at a central portion of the foot. In some implementations, the gait lines **171**A, **171**B are computed for individual steps during a test routine. The gait lines **171**A, **171**B and other gait information can be determined using timing, balance, pressure, force, and motion information obtained from the instrumented footwear **109**A and **109**B.

[0028] FIG. 1E illustrates an example of gait parameters corresponding to components of a stride (e.g., stride **121**) determined by the gait analysis system **113** for one of user's feet based on force information (e.g., gait information **115**A and **115**B) from instrumented footwear (e.g., instrumented footwear **109**A, **109**B). The gait parameters of the stride can include initial contact **127**, loading response **129**, mid stance **131**, terminal stance **133**, and pre-swing **135**, which can be the same as those described above regarding FIG. 1B. As shown in FIG. 1E, a first peak ground reaction force **179** can occur after heel strike (early stance) occurring during the loading response

[0029] Additionally, a local minimum force **181** can occur during mid-stance **131** between the loading response **129** and the terminal stance **133**. Further, a second peak ground reaction force **183** can occur before toe off (late stance) of the pre-swing **135**.

[0030] FIG. **2** shows a system block diagram illustrating an example of a gait analysis system **113**, which can be the same or similar to that described above. The gait analysis system **113** includes hardware and software that perform the processes and functions disclosed herein. The gait analysis system **113** includes a computing device **230**, an input/output (I/O) device **233**, and a storage system **235**. The 1/0 device **233** can include any device that enables an individual (e.g., user **103**) to interact with the computing device **230** (e.g., a user interface) and/or any device that enables the computing device **230** to communicate with one or more other computing devices using any type of communications link. The I/O device **233** can be, for example, a touchscreen display, pointer device, keyboard, etc.

[0031] The storage system **235** can comprise a computer-readable, non-volatile hardware storage device that stores information and program instructions. For example, the storage system **235** can be one or more flash drives and/or hard disk drives. In accordance with aspects of the present disclosure, the storage system **235** can store user profiles **257**, a gait information repository **259**, gait parameters **261**, and reference gait information **263**. The user profiles **257** can include information describing individuals (e.g., user **105**) for which the gait analysis system **113** has collected gait information **115**A, **115**B. The user profiles **257** can comprise demographic and physical information of the users, including identification, age, gender, height, weight, body mass index, pains, injuries, and ailments. The gait information repository **259** can store the gait information **115**A, **115**B generated by the instrumented footwear **109**A, **109**B. For example, the gait information can include force per time data and acceleration per time data from the instrumented footwear **109**A, **109**B. The gait parameters **261** can store information generated by the gait analysis system based on information included in the user profiles **257** and the gait information repository **259**. In some implementations, the gait parameters **261** can include some or all of the information illustrated in FIGS. **5**A, **5**B, and **5**C. The reference gait information **263** can include information relating gait parameters with reference information of gaits affected by ailments. In some implementations, the reference gait information **263** can characterize particular gait parameters or combinations thereof with ailment conditions. For example, gait reference information **263** define a correspondence between gait parameters indicating the force and asymmetry of a subject's gait with a particular ailment and a severity of the ailment.

[0032] In some implementations, the computing device **230** includes one or more processors **239** (e.g., microprocessor, microchip, or application-specific integrated circuit), one or more memory devices **221** (e.g., random-access memory (RAM) and read-only memory (ROM)), one or more 1/0 interfaces **223**, and one or more network interfaces **245**. The memory device **221** can include a local memory (e.g., a RAM and a cache memory) employed during execution of program instructions. Additionally, the computing device **230** includes at least one communication channel **232** (e.g., a data bus) by which it communicates with the 1/0 device **233** and the storage system

[0033] The processor **239** executes computer program instructions (e.g., an operating system and/or application programs), which can be stored in the memory device **221** and/or storage system **235**.

[0034] The processor **239** can also execute computer program instructions of a gait parameter module **271**, a gait analysis module **273**, and a treatment assessment module **275**. The gait parameter module **271** can determine information stored in the gait parameters **261** using the gait information **115**A, **115**B generated by the instrumented footwear **109**A, **109**B and stored in the gait information repository **259**. The gait analysis module **273** can determine correlations between various gait information and gait parameters to characterize users' gaits. For example, the gait analysis module **273** can use Spearman correlations between gait parameters, such as illustrated by the example heatmaps shown in FIGS. **6**A, **6**B, and **6**C. In some implementations, the gait analysis module **273** can determine gait signatures of individual users. The treatment assessment module **275** can determine effectiveness of treatments based on the gait signatures, the gait parameters, the gait information, and the profiles. In some implementations, the treatment assessment module **275** can determine differences between a user's gait signature and reference gait signature stored in gait reference information **263** to assess improvement in a user's gait due to treatment. For example, the treatment assessment

module **275** can compare user's gait line, such as shown in FIG. ID, with a previous gait line, with a reference gait line obtained from afflicted individuals of similar profile (physical and demographic) having a same or similar ailment, and a reference gait line obtained from unafflicted individuals of similar profile.

[0035] It is noted that the computing device **230** can comprise any general-purpose computing article of manufacture capable of executing computer program instructions installed thereon (e.g., a personal computer, server, etc.). However, the computing device **230** is only representative of various possible equivalent-computing devices that can perform the processes described herein. To this extent, in implementations, the functionality provided by the computing device **230** can be any combination of general and/or specific purpose hardware and/or computer program instructions. In each implementation, the program instructions and hardware can be created using standard programming and engineering techniques, respectively.

[0036] The flow diagrams in FIGS. **3** and **4** illustrate examples of the functionality and operation of some implementations of systems, methods, and computer program products according to various implementations consistent with the present disclosure. Each block in the flow diagrams of FIGS. **3** and **4** can represent a module, segment, or portion of program instructions, which includes one or more computer executable instructions for implementing the illustrated functions and operations. In some alternative implementations, the functions and/or operations illustrated in a particular block of the flow diagram can occur out of the order shown in FIGS. **3** and **4**. For example, two blocks shown in succession can be executed substantially concurrently, or the blocks can sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the flow diagram and combinations of blocks in the block can be implemented by special purpose hardware-based systems that perform the specified functions or acts, or combinations of special purpose hardware and computer instructions.

[0037] FIG. **3** illustrates a method **300** of determining reference gait information (e.g., reference gait information **263**) in accordance with some implementations consistent with the present disclosure. At block **307**, the method **300** can include determining gait information (e.g., gait information **115**A, **115**B) of users (e.g., user **105**) performing test routines using instrumented footwear (e.g., instrumented footwear **109**A, **109**B). In some implementations, the users include individuals substantially lacking ailments affecting their gaits. Additionally, in some implementations, the users also include individuals having ailments affecting their gaits. The users can express the ailments in various degrees. For example, the users can have undergone various amounts of treatment and recovery for their ailments. In some implementations, the test routines include walking and standing tests. For example, the test routines can involve testers standing still for about 30 seconds, walking a distance (e.g., distance **119**) at a first, comfortable speed, standing still for about a period of time, walking the distance at a second, slow speed, stand still for the period of time, and walking the distance at a third, fast speed. In some implementations, the distance is greater than or equal to about 10 meters and the standing time can be greater than or equal to about 30 seconds.

[0038] At block **311**, the method **300** determines gait parameters using the gait data collected. at **307**. In some implementations, determining the gait parameters includes, at block **315**, integrating the gait parameters determined at block **311** from the test routines. In some implementations, integrating includes determining means and standard deviations of the gait parameters over the distance used in the test routine. In some implementations, determining the gait parameters also includes, at block **319**, determining components of the gait phases occurring during the test routines using the gait parameters determined at block **311**. The components of the gait phases can be the same or similar to those described above. In some implementations, the gait phases include the stance phase (initial contact, loading response, mid stance, terminal stance pre-swing) and the swing phase (initial swing, mid swing, terming swing). In some implementations, determining the gait parameters also includes, at block **325**, determining gait speed levels (e.g., slow, comfortable, fast) of the gait parameters determined at block **311**. In some implementations, determining the gait parameters also includes, at block **327**, combining the gait parameters determined at **311** at the speed levels determined at block **323**. In some implementations, the gait parameters can include, for each foot of a user, mean gait line length, mean gait line width, mean center of pressure (X-axis, Y-axis, Z-axis), standard deviation of the center of pressure (X-axis, Y-axis, Z-axis), length of bounding box of the center of pressure, width of bounding box of the center of pressure, mean center of pressure velocity, center of pressure trace length, mean total force during the components of the stance phase, maximum total force during the stance phase, average of all maximum of the total force during the stance phase, mean gait cycle time, mean gait cadence, man double support time, mean fraction of double support, mean step duration, mean stance duration, standard deviation of stance duration, mane swing duration, standard deviation of swing duration, mean fraction of stance phase, standard deviation of stance phase, mean fraction of swing duration, force raise, takeoff dynamics, gait direction dynamics, mean stride length, foot flexibility, walking distance, and mean walking speed. For example, the gait parameters can include some or all of those shown in FIGS. SA, SB, and SC.

[0039] At block **331**, the method **300** determines gait symmetries based on the gait parameters determined at blocks **311**. Gait symmetry can indicate whether a user favored one foot over another. At block **335**, the method determines reference gait signatures using the gait parameters determined at **311** and the gait symmetries determined at block **331**. At block **339**, the method determines correlations between the gait parameters determined at **311**. The correlations between gait parameters can be calculated by deriving Spearman correlations between the raw values for the gait parameters. Parameters that cluster together are highly correlative, indicating that they measure very similar trends in the walk. Parameters the have low intraindividual variability measured with intraclass correlation (ICC). In some implementations, between about 5 to about 7 clusters of the 61 raw gait parameters that can be used to describe similar walking trends. These variables often have similar names, or are measuring the same motion bilaterally (left vs right foot), Most parameters in this study have high intraclass correlation (e.g., low intraindividual variability). Endpoints that are summary metrics of multiple parameters control for noise of an individual parameter, so this analysis

may help compute these endpoints. Identifying variables with high intraclass correlation helps refine candidate endpoints for comparing clinical groups. This analysis can help inform asymmetry in walking patterns within an individual.

[0040] At block **343**, the method **300** determines correlations between the gait parameters determined at **311** and the gait symmetries determined at block **331**. For example, the system can use linear modeling and principle component analysis (PCA) to determine relationships between the gait parameters and clinical and demographic variables.

[0041] FIG. **4** shows a flow block diagram illustrating an example of a method for evaluating effectiveness of treatments in accordance with aspects of the present disclosure. At block **405**, the method **400** can include determining gait information (e.g., gait information **115**A, **115**B) of a user (e.g., user **105**) performing an evaluation routine using instrumented footwear (e.g., instrumented footwear **109**A, **109**B). In some implementations, the user can be a user afflicted with an ailment and who may be receiving treatments for the ailment. In some implementations, the evaluation routine can be the same or similar to the test routine previously described herein regarding FIG. **3**, block **307**.

[0042] At block **409**, the method **400** determines gait parameters using the gait data collected. at **405** in a same or similar manner to that previously described herein regarding FIG. **3**, block **311**. As detailed above, in some implementations, determining the gait parameters can in include integrating the gait parameters at block **413**, determining components of the gait phases at block **417**, determining gait speed levels at block **421**, and combining the gait parameters at the respective speed levels at block **425**.

[0043] At block **429**, the method **400** determines gait symmetries based on the gait parameters determined at block **409**. At block **433**, the method determine reference gait signatures using the gait parameters determined at **411** and the gait symmetries determines at block **431**. At block **437**, the method **400** determines treatment effects based on the signatures determined at block **433** and the gait parameters determined at block **409**. In some implementations, the patient's gait signature and gait parameters are compared to previous gait signatures to identify changes. For example, the comparison can determine whether treatment of the patient has altered their gait signature. In some implementations, the patient's gait signature and gait parameters can be compared to reference gait signatures and gait parameters to determine similarities. For example, the comparison can determine whether the patient's gait signature and gait parameter are similar to reference gait signatures and gait parameters of different levels of affliction, such as different degrees of osteoarthritis.

[0044] FIGS. **5**A, **5**B, and **5**C show example gait parameters in accordance with aspects of the present disclosure. The gait parameters shown in FIGS. **5**A, **5**B, and **5**C can be the same or similar to those previously described above. In some implementations, the gait parameters shown in FIGS. **5**A, **5**B, and **5**C include information derived from the information obtained directly from the sensors of the instrumented footwear (e.g., instrumented footwear **109**A, **109**B). Additionally, the gait parameters shown in FIGS. **5**A, **5**B, and **5**C can include information directly obtained from the sensors of the instrumented footwear. It is understood that some can user some or all of the gait parameters shown in FIGS. **5**A, **5**B, and **5**C and can include other suitable parameters describing aspects of a user's gait.

[0045] FIGS. **6**A, **6**B, and **6**C show heat maps illustrating correlations between gait parameters in accordance with aspects of the present disclosure. FIG. **6**A illustrates correlations among gait parameters with a normal (e.g., medium) walking speed group. FIG. **6**B illustrates clustering of gait parameters for the normal walking speed group demonstrating that have unique walking signature. FIG. **6**C illustrates clustering within the slow, normal, and fast speed group demonstrating that individuals have unique walking signature.

[0046] The heatmaps shown in FIGS. **6**A, **6**B, and **6**C illustrate variation in gait parameters using unsupervised hierarchical clustering to group parameter that show trends based on clinical and demographic variables. In the heatmaps, clinical and demographic variables relate to each other (e.g., confound) and similar row variables cluster together. Columns of the heat maps represent individual test routines, wherein individual users (e.g., user **105**) cluster with themselves. In some implementations, the gait parameters can include about 45 parameters corresponding to gait report and about 16 parameters corresponding to balance. Between about 5 and about 7 clusters of about 61 raw gait parameters that can be used to identify similar walking trends. For each parameter, the gait analysis system (e.g., gait analysis system **113**) can calculate the average for individual users within each speed level. These parameters are in the same category, or are measuring the same motion bilaterally (left vs right foot). For each pair of parameters, the gait analysis system can calculate Spearman correlations within individual speed levels. The Spearman correlations can be used as a distance metric to perform the unsupervised hierarchical clustering to visualize trends. Further, principle components analysis (ordination) reduces variables from 61 dimensions to two dimensions (principle components), while retaining virtually all the variation in the original data. The above analysis can inform asymmetry in walking patterns of users (differences in left vs right foot measurements). Additionally, individual users can be identified through their unique walking signature.

[0047] The present disclosure is not to be limited in terms of the particular implementation described in this application, which are intended as illustrations of various aspects. Many modifications and variations can be made without departing from its spirit and scope, as will be apparent to those skilled in the art. Functionally equivalent methods and apparatuses within the scope of the disclosure, in addition to those enumerated herein, will be apparent to those skilled in the art from the foregoing descriptions. Such modifications and variations are intended to fall within the scope of the appended claims. The present disclosure is to be limited only by the terms of the appended claims, along with the full scope of equivalents to which such claims are entitled. It is also to be understood that the terminology used herein is for the purpose of describing examples of implementations, and is not intended to be limiting.

[0048] With respect to the use of substantially any plural and/or singular terms herein, those having skill in the art can translate from the plural to the singular and/or from the singular to the plural as is appropriate to the context and/or application. The various singular/plural permutations may be expressly set forth herein for sake of clarity.

[0049] It will be understood by those within the art that, in general, terms used herein, and especially in the appended claims (e.g., bodies of the appended claims) are generally

intended as "open" terms (e.g., the term "including" should be interpreted as "including but not limited to," the term "having" should be interpreted as "having at least," the term "includes" should be interpreted as "includes but is not limited to," etc.). It will be further understood by those within the art that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases "at least one" and "one or more" to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim recitation to implementations containing only one such recitation, even when the same claim includes the introductory phrases "one or more" or "at least one" and indefinite articles such as "a" or "an" (e.g., "a" and/or "an" should be interpreted to mean "at least one" or "one or more"); the same holds true for the use of definite articles used to introduce claim recitations. In addition, even if a specific number of an introduced claim recitation is explicitly recited, those skilled in the art will recognize that such recitation should be interpreted to mean at least the recited number (e.g., the bare recitation of "two recitations," without other modifiers, means at least two recitations, or two or more recitations). Furthermore, in those instances where a convention analogous to "at least one of A, B, and C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, and C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, Band C together, and/or A, B, and C together, etc.). In those instances where a convention analogous to "at least one of A, B, or C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, or C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, Band C together, and/or A, B, and C together, etc.). It will be further understood by those within the art that virtually any disjunctive word and/or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms. For example, the phrase "A or B" will be understood to include the possibilities of "A" or "B" or "A and B." In addition, where features or aspects of the disclosure are described in terms of Markush groups, those skilled in the art will recognize that the disclosure is also thereby described in terms of any individual member or subgroup of members of the Markush group.

1. A gait analysis system comprising:

a processor; and

a computer-readable data storage device storing program instructions that, when executed by the processor, control the gait analysis system to:

receive gait information of a user;

determine a plurality of gait parameters based on the gait information;

determine correlations between the plurality of gait parameters;

identify a subset of the plurality of gait parameters having an intraclass correlation above a correlation threshold;

determine a gait signature of the user based on the subset of the plurality of gait parameters;

compare the gait signature of the user to a reference gait signature obtained using the subset of the plurality of gait parameters for afflicted individuals and to a reference gait signature obtained using the subset of the plurality of gait parameters for unafflicted individuals to identify a degree of affliction in the user's gait; and

determine a treatment effect on the user's gait based on the identifying the degree of affliction.

2. The gait analysis system of claim **1**, wherein the gait information is received from one or more mobile sensors including a plurality of force transducers or a multi-axis accelerometer.

3. The gait analysis system of claim **1**, wherein the plurality of gait parameters include a standard deviation of stride gait lines corresponding to a stride, or a mean cycle time.

4. The gait analysis system of claim **1**, wherein the plurality of gait parameters comprise one or more of:

a first peak ground reaction force representing an occurrence of a heel strike component of a stride of the user;

a local minimum force representing an occurrence of a terminal stance component of the stride of the user; or

a second peak ground reaction force representing an occurrence of a pre-swing component of the stride of the user.

5. The gait analysis system of claim **1**, wherein determining the plurality of gait parameters includes integrating the plurality of gait parameters determined over a distance of a test routine.

6. The gait analysis system of claim **1**, wherein determining the plurality of gait parameters includes integrating the plurality of gait parameters determined over a distance of a test routine, and wherein determining the plurality of gait parameters further includes determining components of a stride of the user during the test routine.

7. The gait analysis system of claim **1**, wherein determining the plurality of gait parameters includes integrating the plurality of gait parameters determined over a distance of a test routine, wherein determining the plurality of gait parameters further includes determining components of a stride of the user during the test routine, and wherein determining the plurality of gait parameters further includes determining respective gait speed levels of the components of the stride of the user.

8. The gait analysis system of claim **1**, wherein determining the plurality of gait parameters includes integrating the plurality of gait parameters determined over a distance of a test routine, wherein determining the plurality of gait parameters further includes determining components of a stride of the user during the test routine, wherein determining the plurality of gait parameters further includes determining respective gait speed levels of the components of the stride of the user, and wherein determining the respective gait speed levels comprises selecting the respective gait speed levels from one or more of: a slow speed level, a normal speed level, or a fast speed level.

9. The gait analysis system of claim 1, wherein determining the plurality of gait parameters includes integrating the plurality of gait parameters determined over a distance of a test routine, wherein determining the plurality of gait parameters further includes determining components of a stride of the user during the test routine, wherein determining the plurality of gait parameters further includes determining respective gait speed levels of the components of the stride of the user, wherein determining the respective gait speed levels comprises selecting the respective gait speed levels from one or more of: a slow speed level, a normal speed level, or a fast speed level, and wherein determining the plurality of gait parameters further includes combining the plurality of gait parameters based on the respective gait speed levels of the plurality of gait parameters.

10. A method for gait analysis, the method comprising:

receiving gait information of a user;

determining a plurality of gait parameters based on the gait information;

determining correlations between the plurality of gait parameters;

identifying a subset of the plurality of gait parameters having an intraclass correlation above a correlation threshold;

determining a gait signature of the user based on the subset of the plurality of gait parameters;

comparing the gait signature of the user to a reference gait signature obtained using the subset of the plurality of gait parameters for afflicted individuals and to a reference gait signature obtained using the subset of the plurality of gait parameters for unafflicted individuals to identify a degree of affliction in the user's gait; and

determining a treatment effect on the user's gait based on the identifying the degree of affliction.

11. The method of claim 10, wherein the gait information is based on gait data from a plurality of force transducers and a multi-axis accelerometer included in an instrumented footwear.

12. The method of claim 10, wherein the plurality of gait parameters include a gait line, a standard deviation of stride gait lines corresponding to a stride, or a mean cycle time.

13. The method of claim 10, wherein the plurality of gait parameters comprise one or more of:

a first peak ground reaction force representing an occurrence of a heel strike component of a stride of the user;

a local minimum force representing an occurrence of a terminal stance component of the stride of the user; and

a second peak ground reaction force representing an occurrence of a pre-swing component of the stride of the user.

14. The method of claim 10, wherein determining the plurality of gait parameters includes integrating the plurality of gait parameters determined over a distance of a test routine.

15. The method of claim 10, wherein determining the plurality of gait parameters includes integrating the plurality of gait parameters determined over a distance of a test routine, and wherein determining the plurality of gait parameters further includes determining components of a stride of the user during the test routine.

16. The method of claim 10, wherein determining the plurality of gait parameters includes integrating the plurality of gait parameters determined over a distance of a test routine, wherein determining the plurality of gait parameters further includes determining components of a stride of the user during the test routine, and wherein determining the plurality of gait parameters further includes determining respective gait speed levels of the components of the stride of the user.

17. The method of claim 10, wherein determining the plurality of gait parameters includes integrating the plurality of gait parameters determined over a distance of a test routine, wherein determining the plurality of gait parameters further includes determining components of a stride of the user during the test routine, wherein determining the plurality of gait parameters further includes determining respective gait speed levels of the components of the stride of the user, and wherein determining the respective gait speed levels comprises selecting the respective gait speed levels from a set comprising: a slow speed level, a normal speed level, and a fast speed level.

18. A computer program product of a gait analysis system including an instrumented footwear and one or more sensors, the computer program product comprising a computer-readable data storage device storing program instructions that, when executed by a computer processor, cause the gait analysis system to perform operations comprising:

receiving one or more signals from one or more sensors associated with an instrumented footwear associated with a user performing a test routine, the one or more sensors including an accelerometer or a pressure sensor;

determining gait information in response to the one or more signals;

determining a plurality of gait parameters based on the gait information;

determining correlations between the plurality of gait parameters;

identifying a subset of the plurality of gait parameters having an intraclass correlation above a correlation threshold;

determining a gait signature of the user based on the subset of the plurality of gait parameters;

comparing the gait signature of the user to a reference gait signature obtained using the subset of the plurality of gait parameters for afflicted individuals and to a reference gait signature obtained using the subset of the plurality of gait parameters for unafflicted individuals to identify a degree of affliction in the user's gait; and

determining a treatment effect on the user's gait based on the identifying the degree of affliction.

19. The computer program product of claim 18, wherein determining the plurality of gait parameters further comprises:

determining components of a stride of the user during the test routine;

determining respective gait speed levels of the components of the stride of the user from a set comprising: a slow speed level, a normal speed level, and a fast speed level; and

combining the plurality of gait parameters based on the respective gait speed levels of the plurality of gait parameters.

20. The computer program product of claim 18, wherein a treatment associated with the treatment effect is provided to the user prior to performing the test routine.

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