US009763604B1

(12) **United States Patent**
Berme et al.

(10) **Patent No.: US 9,763,604 B1**
(45) **Date of Patent: Sep. 19, 2017**

(54) **GAIT PERTURBATION SYSTEM AND A METHOD FOR TESTING AND/OR TRAINING A SUBJECT USING THE SAME**

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(73) Assignee: **Bertec Corporation**, Columbus, OH (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/488,472**

(22) Filed: **Apr. 15, 2017**

Related U.S. Application Data

(63) Continuation-in-part of application No. 15/095,040, filed on Apr. 9, 2016, now Pat. No. 9,622,686.

(51) **Int. Cl.**
A61B 5/11 (2006.01)
A63B 26/00 (2006.01)

(52) **U.S. Cl.**
CPC ***A61B 5/112*** (2013.01); ***A63B 26/003*** (2013.01)

(58) **Field of Classification Search**
CPC A61B 5/112; A63B 26/003
See application file for complete search history.

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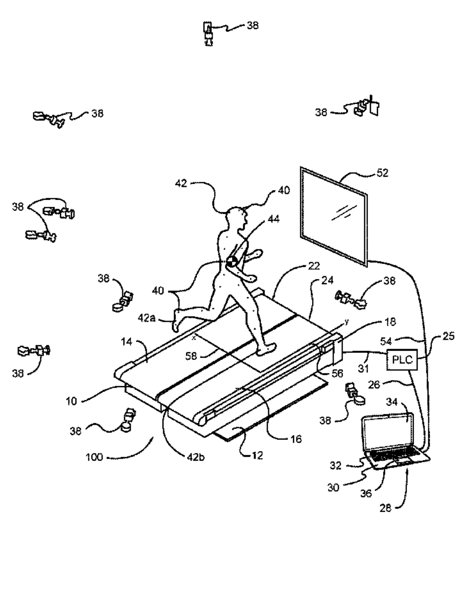
Primary Examiner — Sundhara Ganesan
(74) *Attorney, Agent, or Firm* — The Law Office of Patrick F. O'Reilly III, LLC

(57) **ABSTRACT**

A balance and/or gait perturbation system is disclosed herein. The balance and/or gait perturbation system includes a balance and/or gait perturbation device and a data processing device. The balance and/or gait perturbation device includes one or more displaceable components configured to be displaced at a plurality of different positions, and having one or more surfaces for receiving one or more respective limbs of the person; and one or more first actuators coupled to the one or more displaceable components to adjust the displacement position of the one or more displaceable components. The data processing device is configured to generate a stochastic signal for introducing a perturbation to the one or more displaceable components, and to control the displacement position of the one or more displaceable components using the stochastic signal such that the one or more displaceable components perturb a balance and/or gait of the person.

20 Claims, 22 Drawing Sheets



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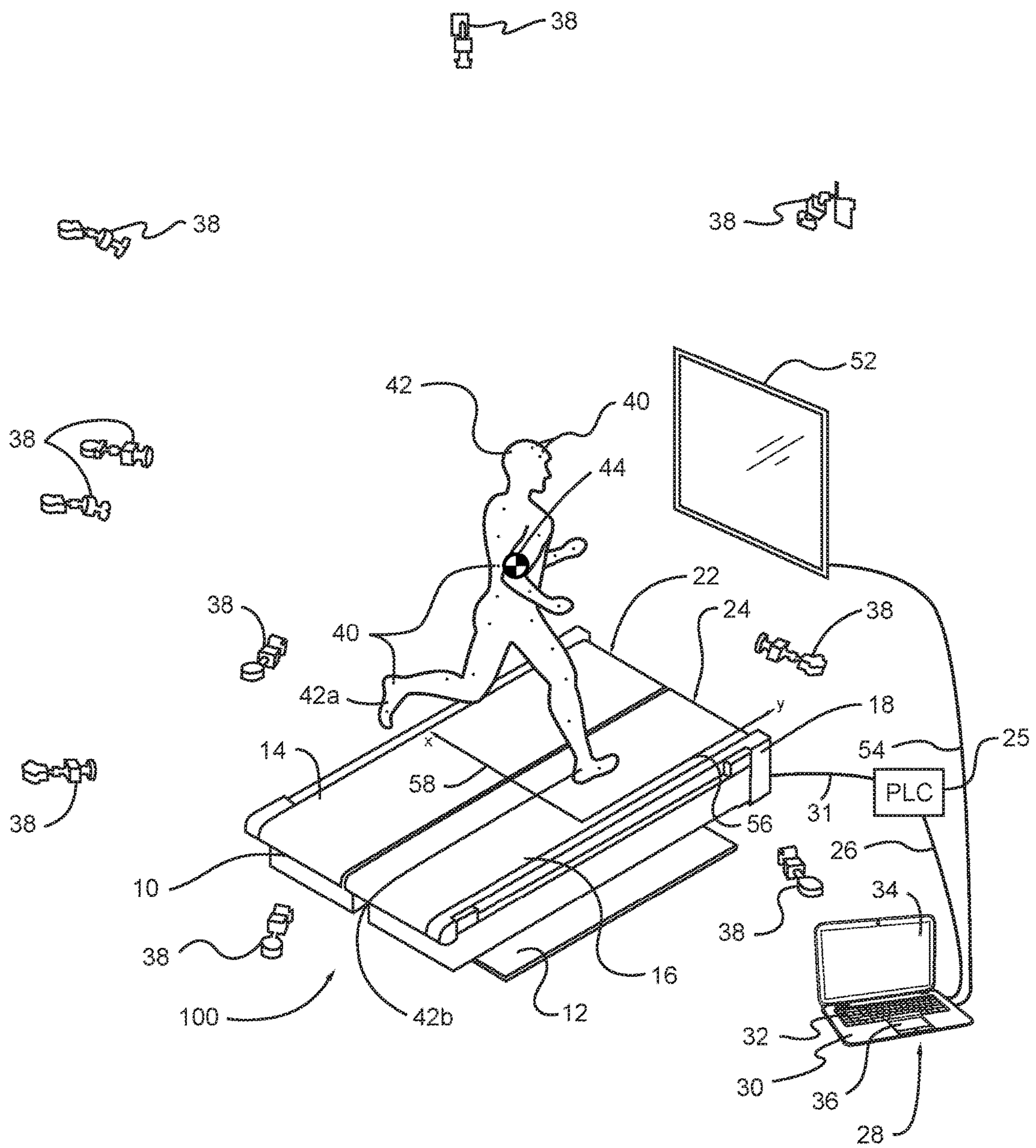
38
38
38
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42
40
44
38
40
22
24
38
38
42a
y
18
14
x
54
25
58
PLC
38
56
31
10
26
34
38
38
16
100
42b
12
32
30
36
28

FIG. 1

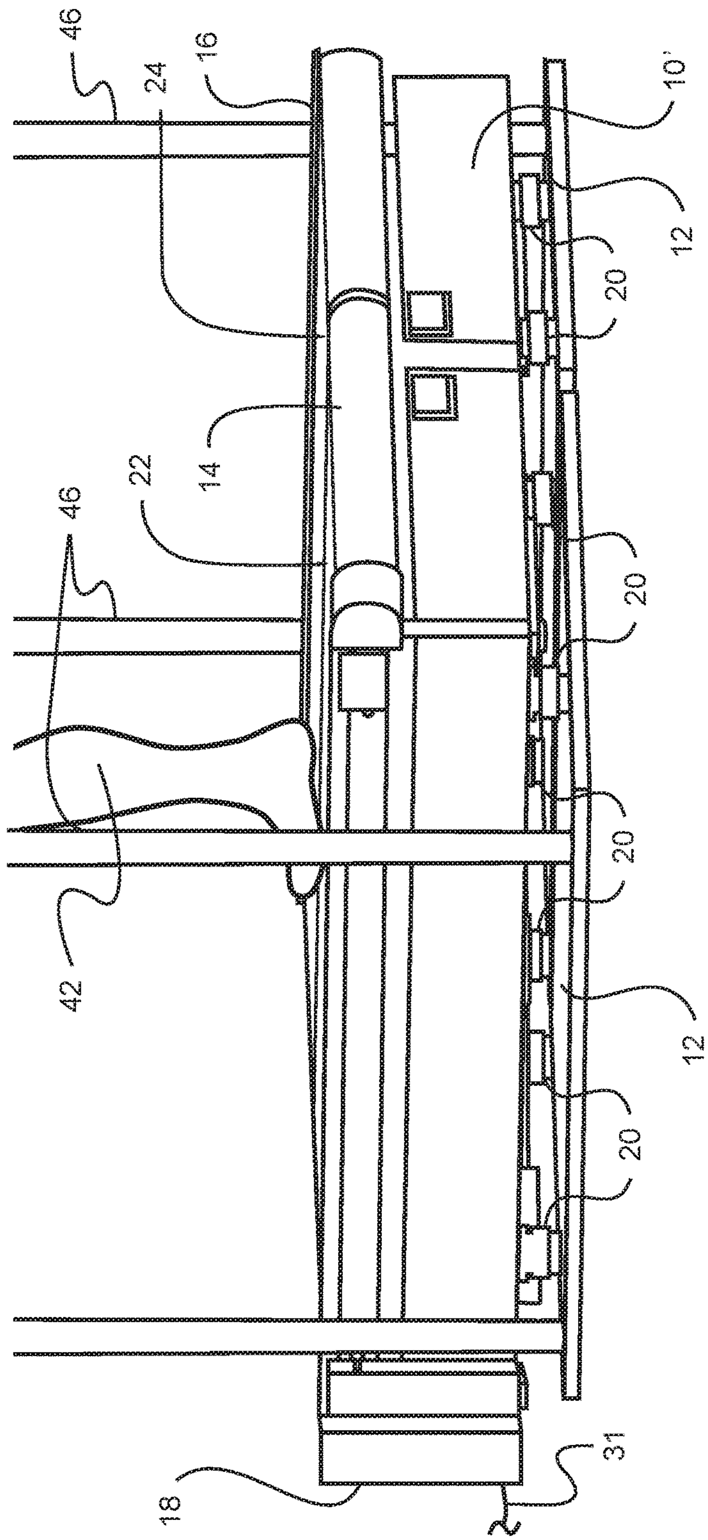


FIG. 2

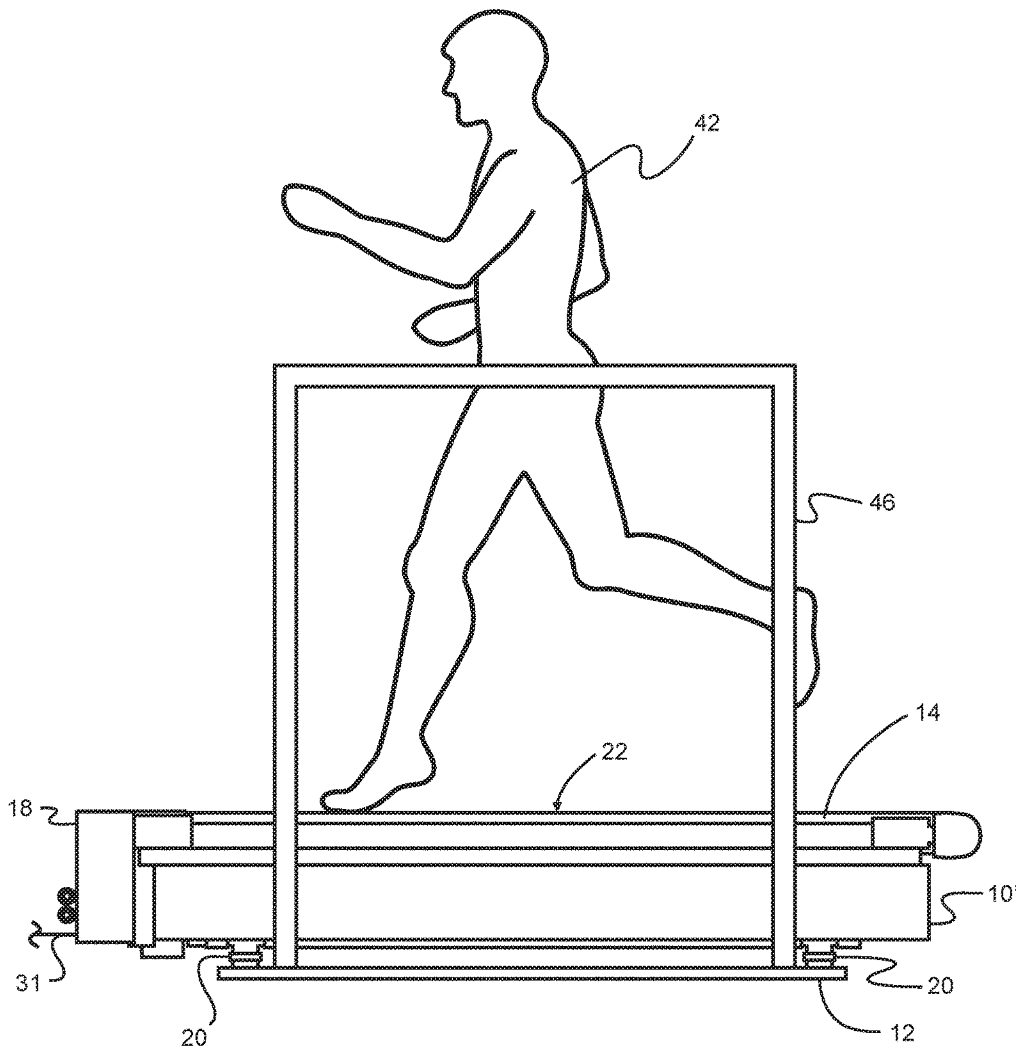


FIG. 3

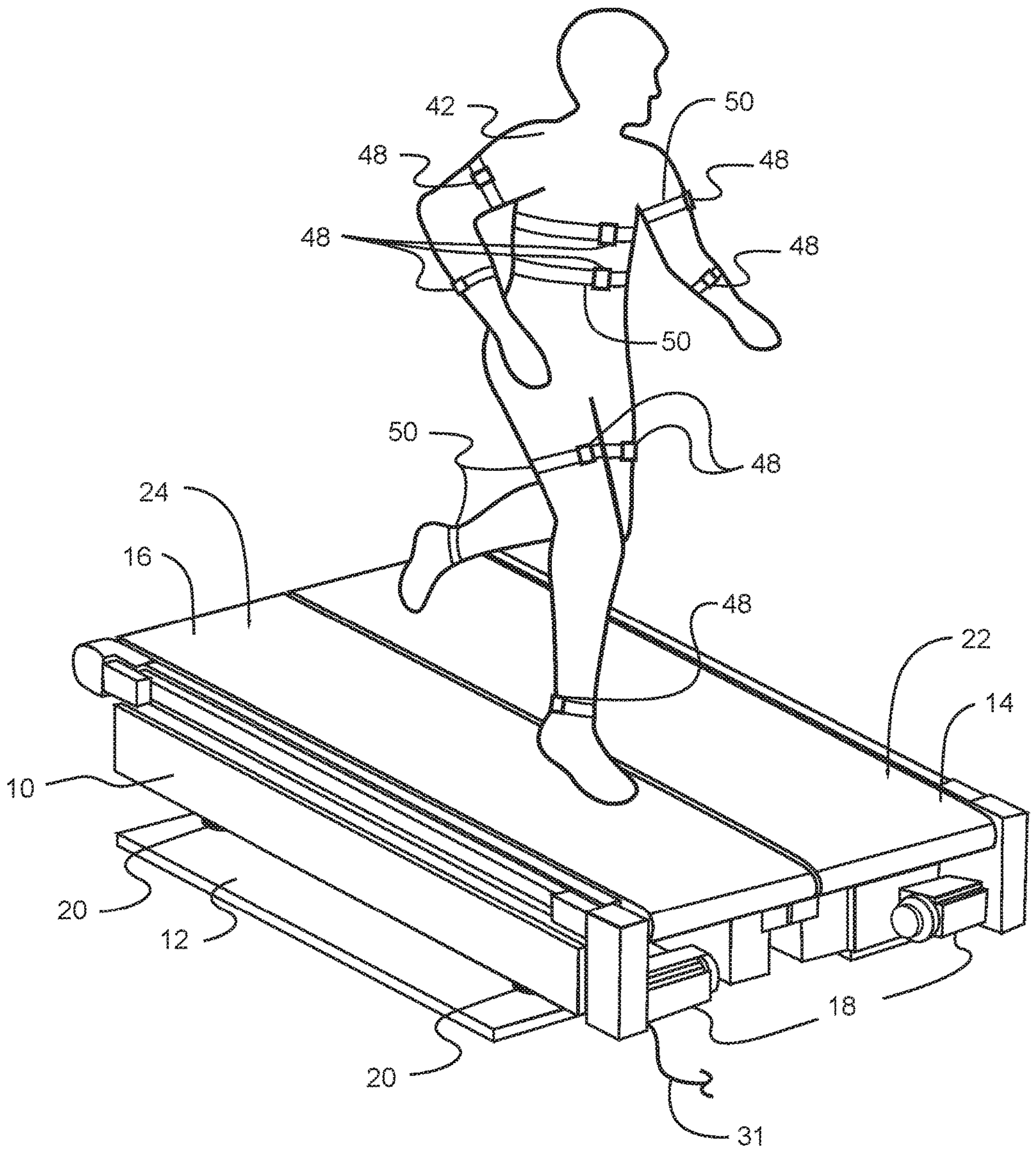


FIG. 4

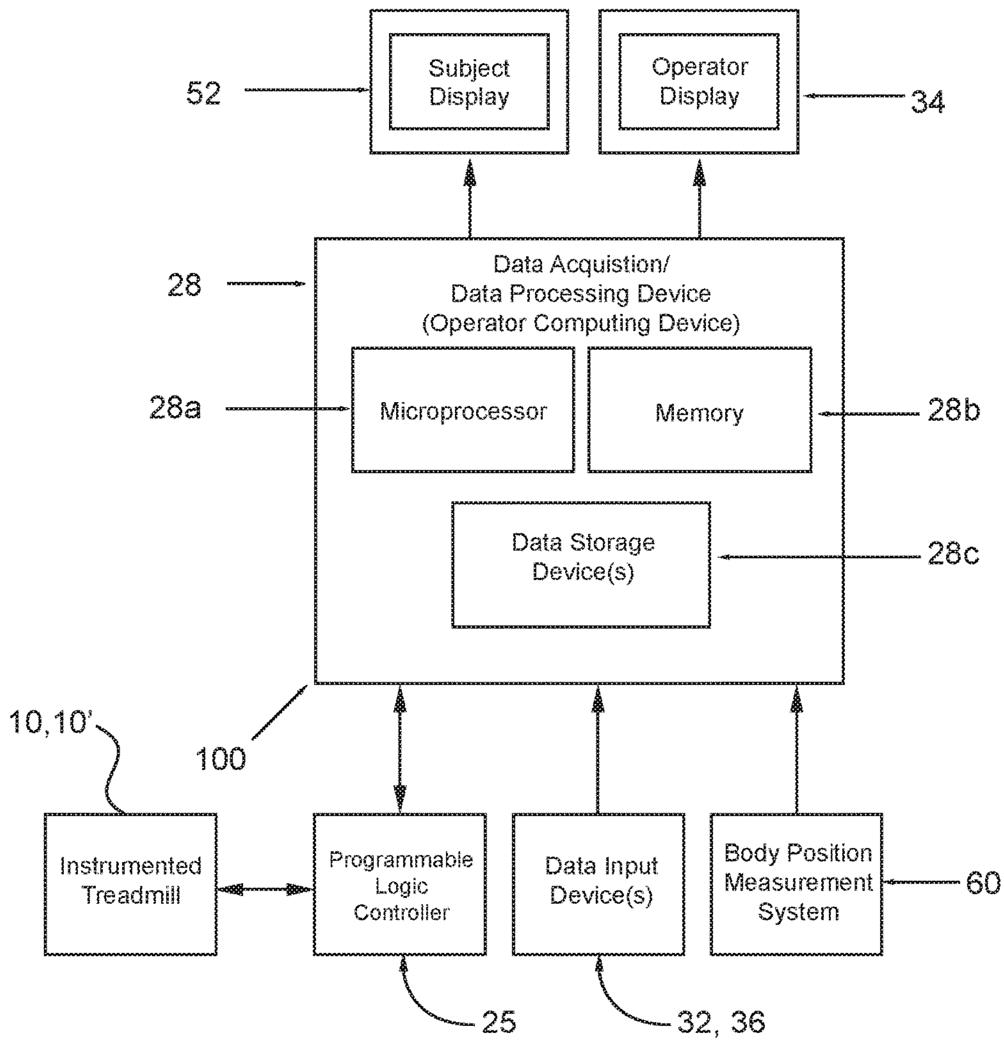

52
Subject Display
Operator Display
34
28
Data Acquistion/
Data Processing Device
(Operator Computing Device)
28a
Microprocessor
Memory
28b
Data Storage Device(s)
28c
10,10'
100
Instrumented Treadmill
Programmable Logic Controller
Data Input Device(s)
Body Position Measurement System
60
25
32, 36

FIG. 5

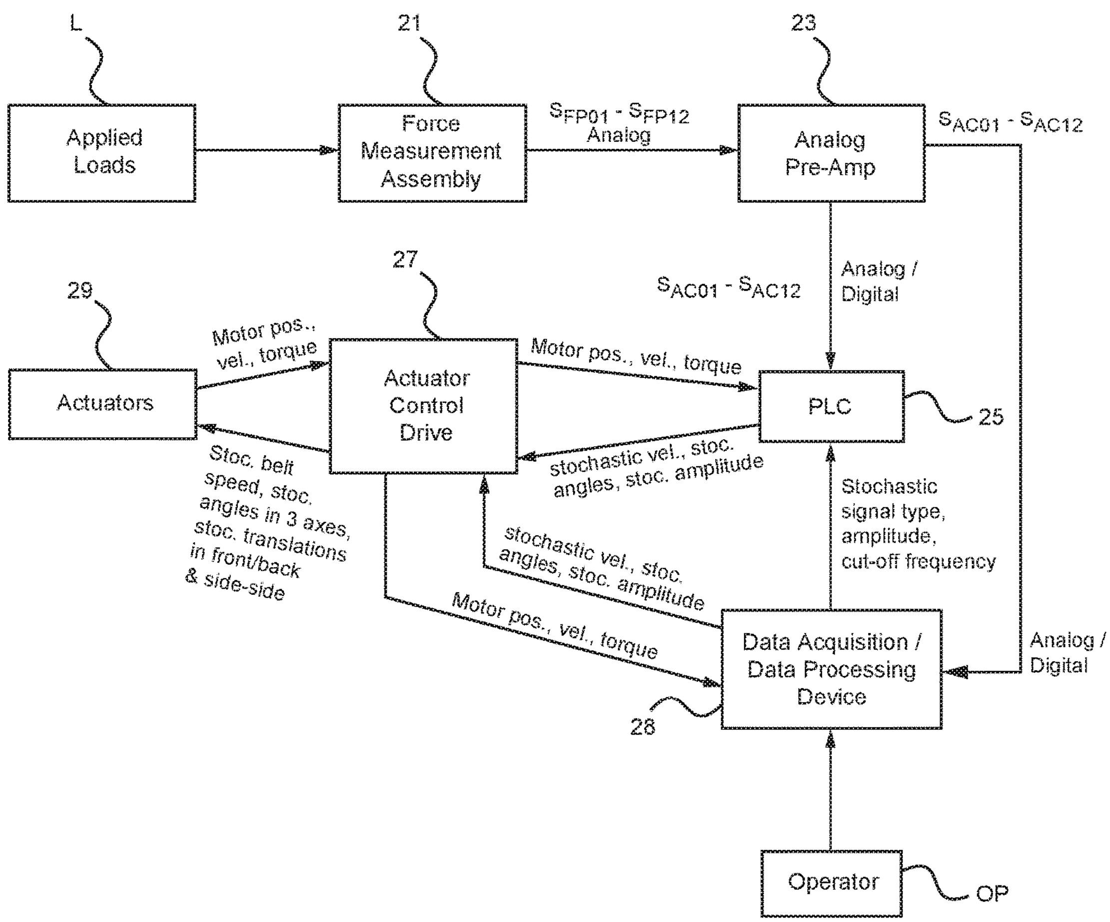

L
21
23
Applied Loads
Force Measurement Assembly
S_{FP01} - S_{FP12} Analog
Analog Pre-Amp
S_{AC01} - S_{AC12}
27
29
S_{AC01} - S_{AC12}
Analog / Digital
Actuators
Motor pos., vel., torque
Actuator Control Drive
Motor pos., vel., torque
PLC
25
stochastic vel., stoc. angles, stoc. amplitude
Stoc. belt speed, stoc. angles in 3 axes, stoc. translations in front/back & side-side
Stochastic signal type, amplitude, cut-off frequency
stochastic vel., stoc. angles, stoc. amplitude
Motor pos., vel., torque
Data Acquisition / Data Processing Device
Analog / Digital
28
Operator
OP

FIG. 6

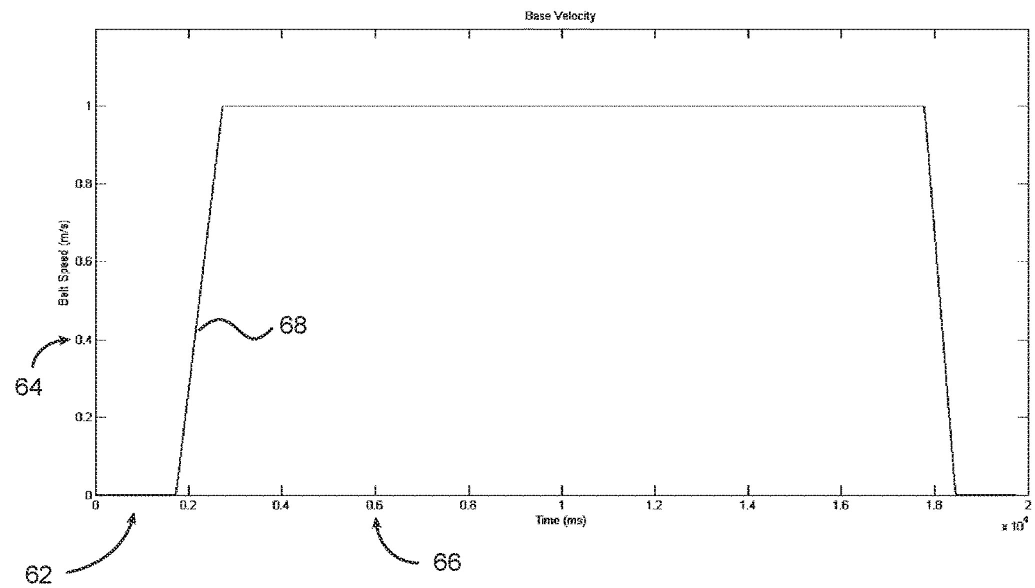

Base Velocity
Belt Speed (m/s)
Time (ms)
x 10^4
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
62
64
66
68

FIG. 7

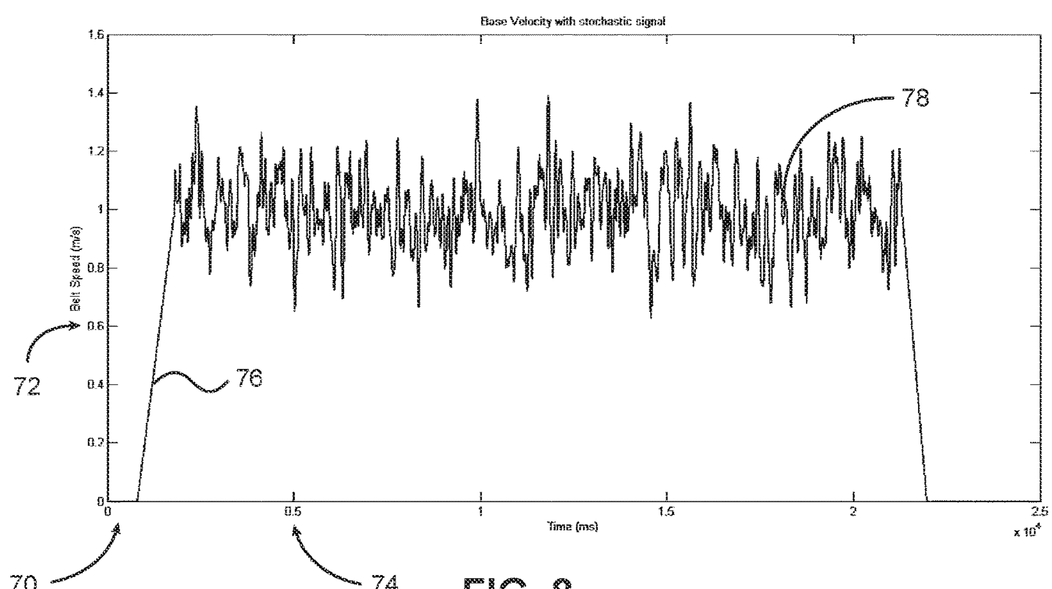

Base Velocity with stochastic signal
Belt Speed (m/s)
Time (ms)
x 10^4
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0.5
1.5
2
2.5
70
72
74
76
78

FIG. 8

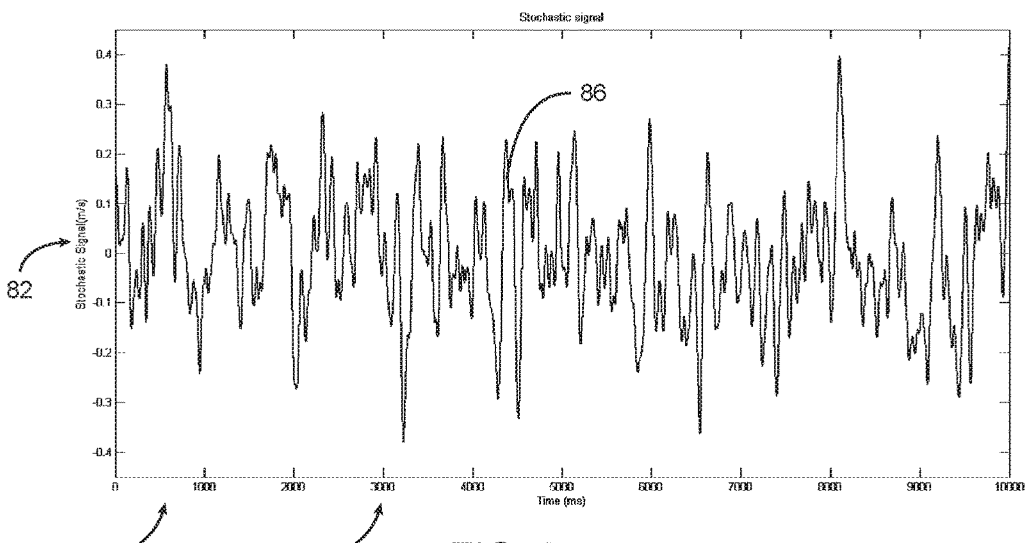

Stochastic signal
86
82
Stochastic Signal (m/s)
Time (ms)
80
84

FIG. 9

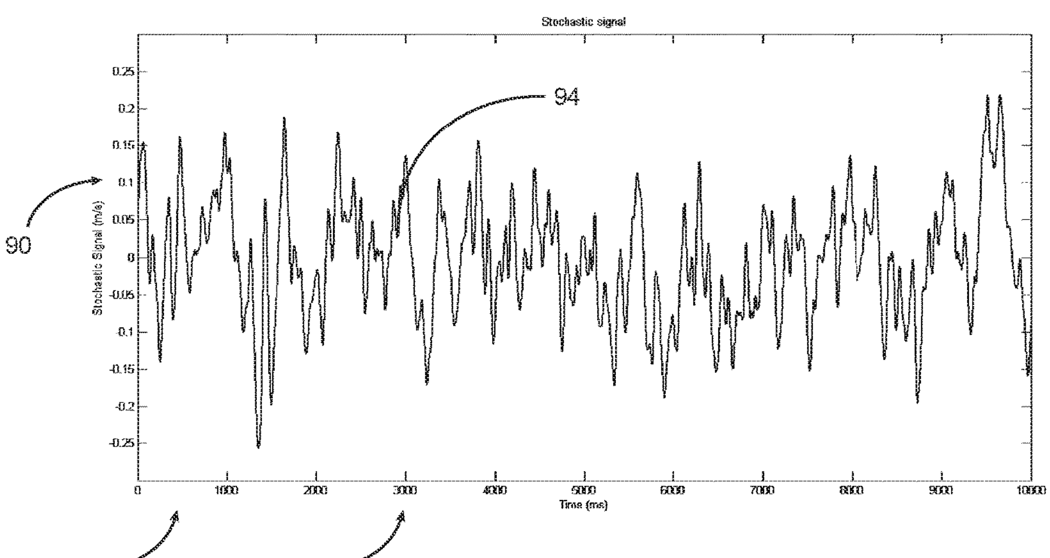

Stochastic signal
94
90
Stochastic Signal (m/s)
Time (ms)
88
92

FIG. 10

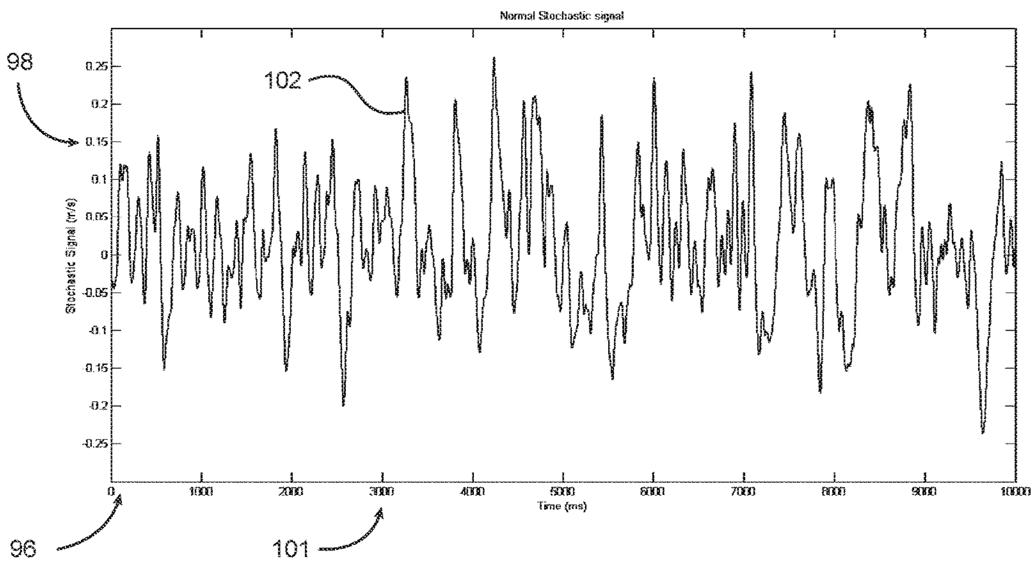

Normal Stochastic signal
98
102
Stochastic Signal (m/s)
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Time (ms)
96
101

FIG. 11

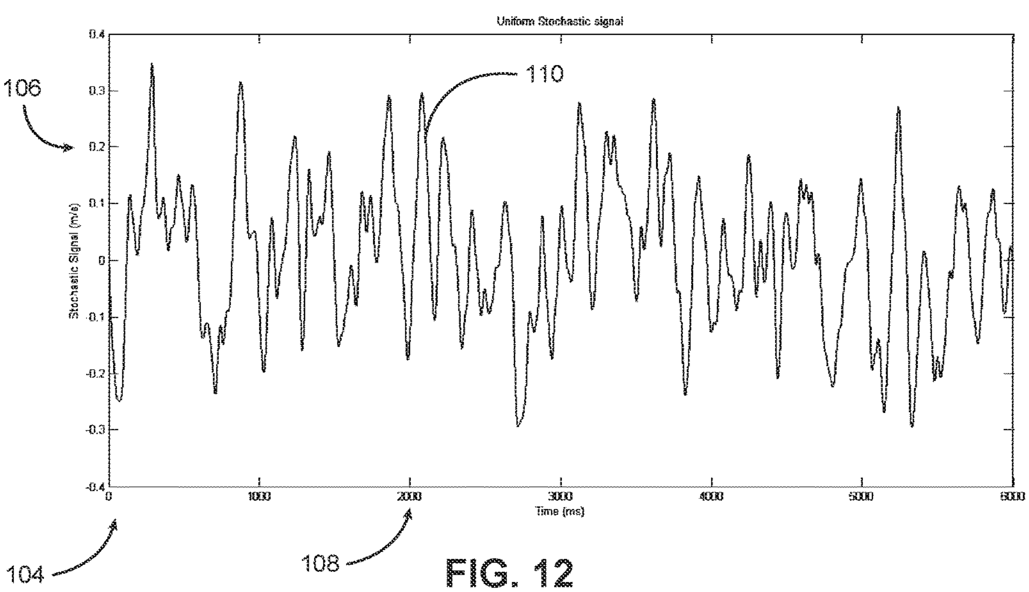

Uniform Stochastic signal
106
110
Stochastic Signal (m/s)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
0
1000
2000
3000
4000
5000
6000
Time (ms)
104
108

FIG. 12

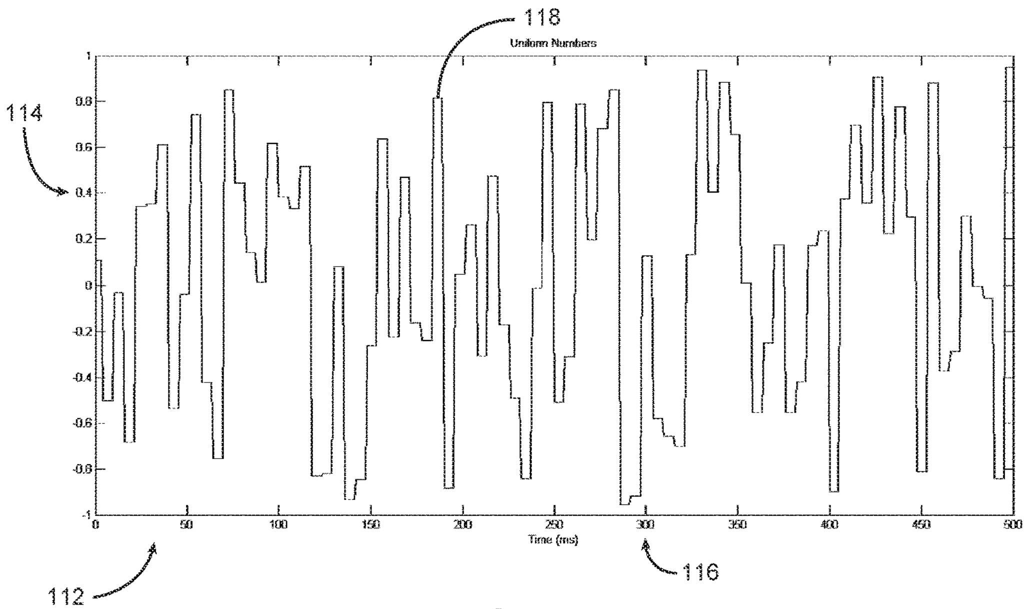

118
Uniform Numbers
114
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
50
100
150
200
250
300
350
400
450
500
Time (ms)
112
116

FIG. 13

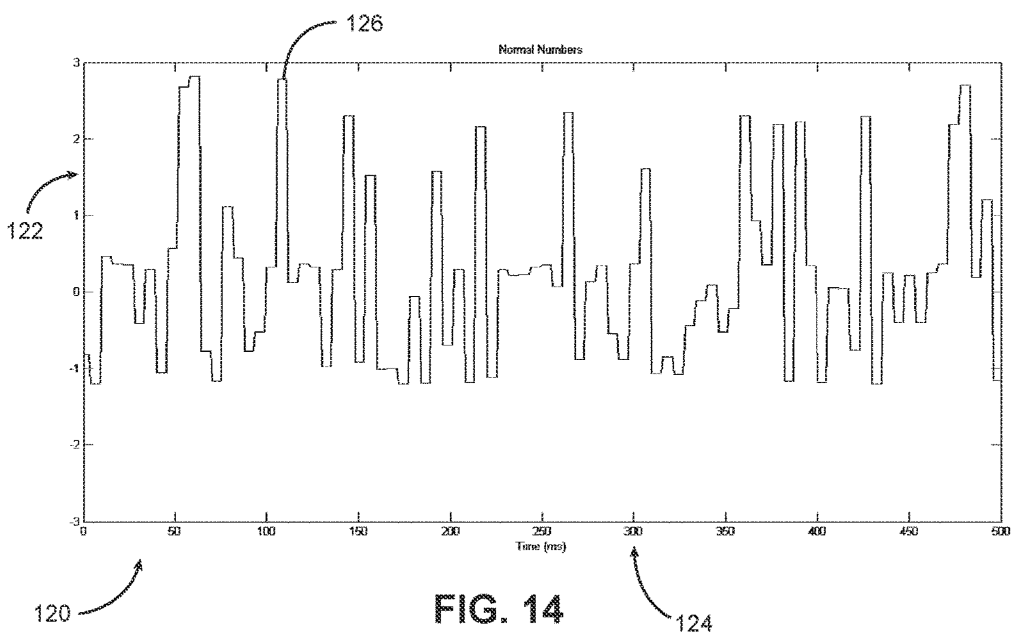

126
Normal Numbers
122
3
2
1
0
-1
-2
-3
0
50
100
150
200
250
300
350
400
450
500
Time (ms)
120
124

FIG. 14

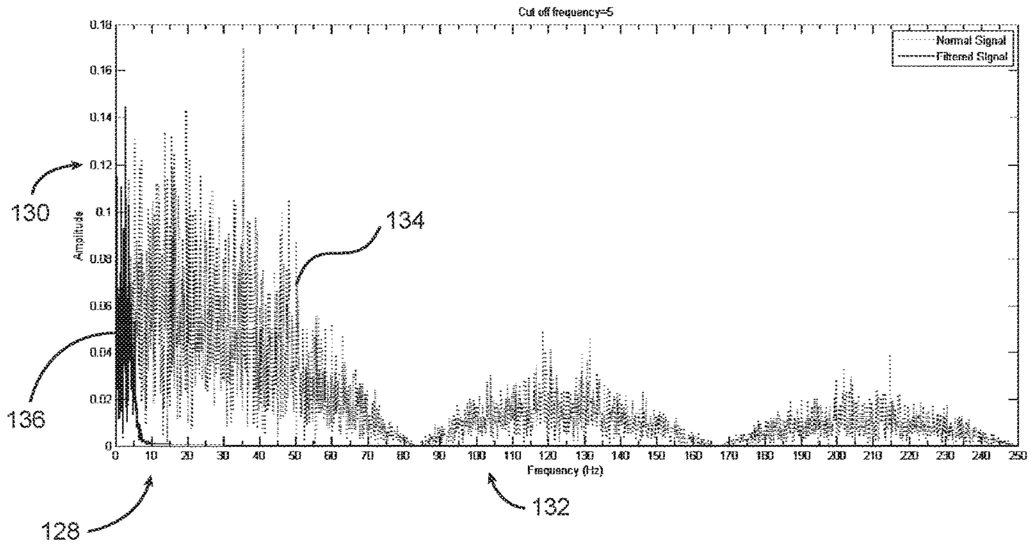

Cut off frequency=5
Normal Signal
Filtered Signal
Amplitude
Frequency (Hz)
130
134
136
128
132

FIG. 15

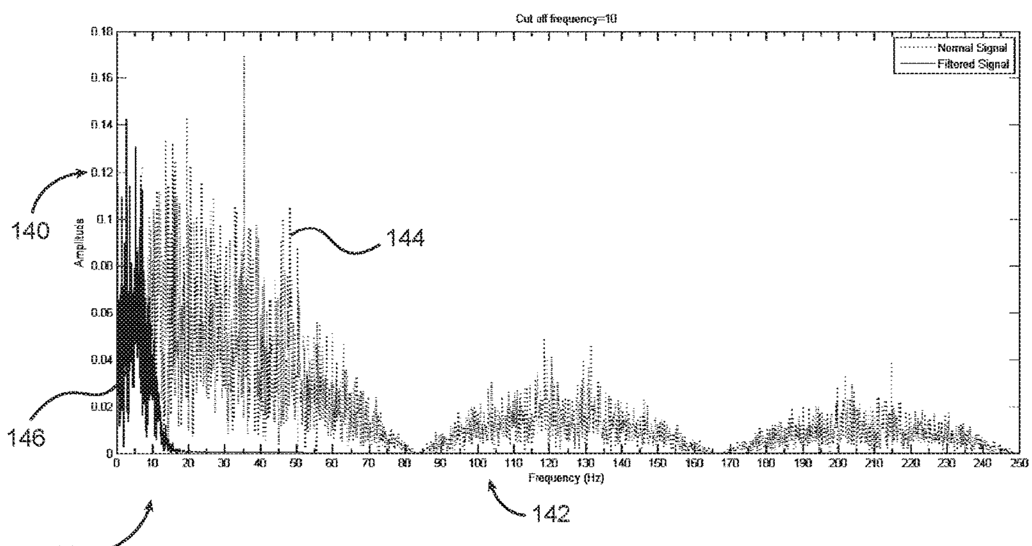
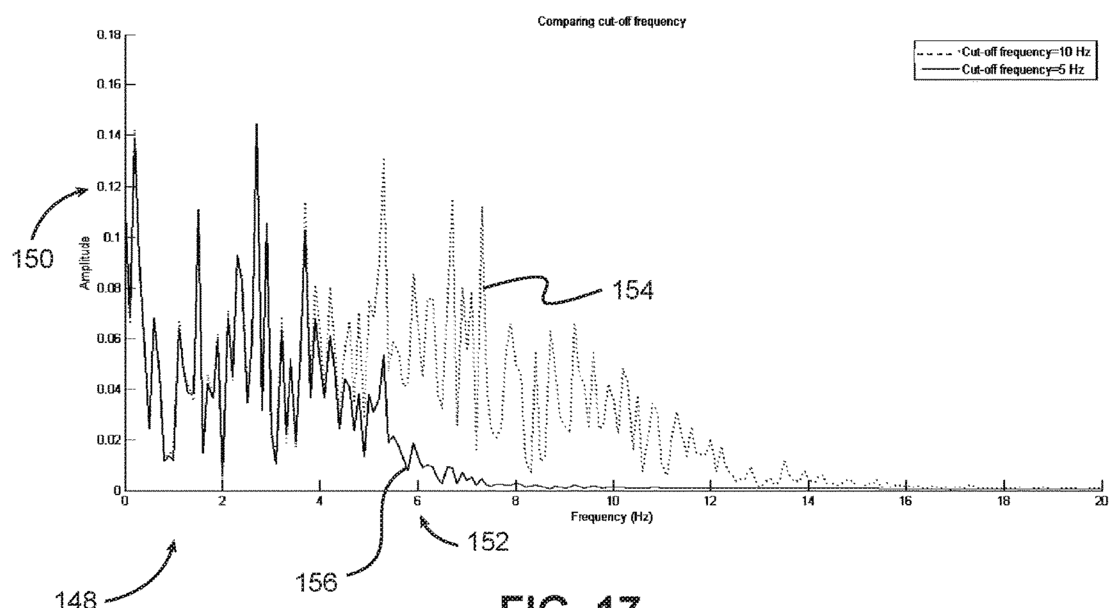

Cut off frequency=10
Normal Signal
Filtered Signal
Amplitude
Frequency (Hz)
140
144
146
138
142

FIG. 16



Comparing cut-off frequency
Cut-off frequency=10 Hz
Cut-off frequency=5 Hz
Amplitude
Frequency (Hz)
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
2
4
6
8
10
12
14
16
18
20
150
154
148
156
152

FIG. 17

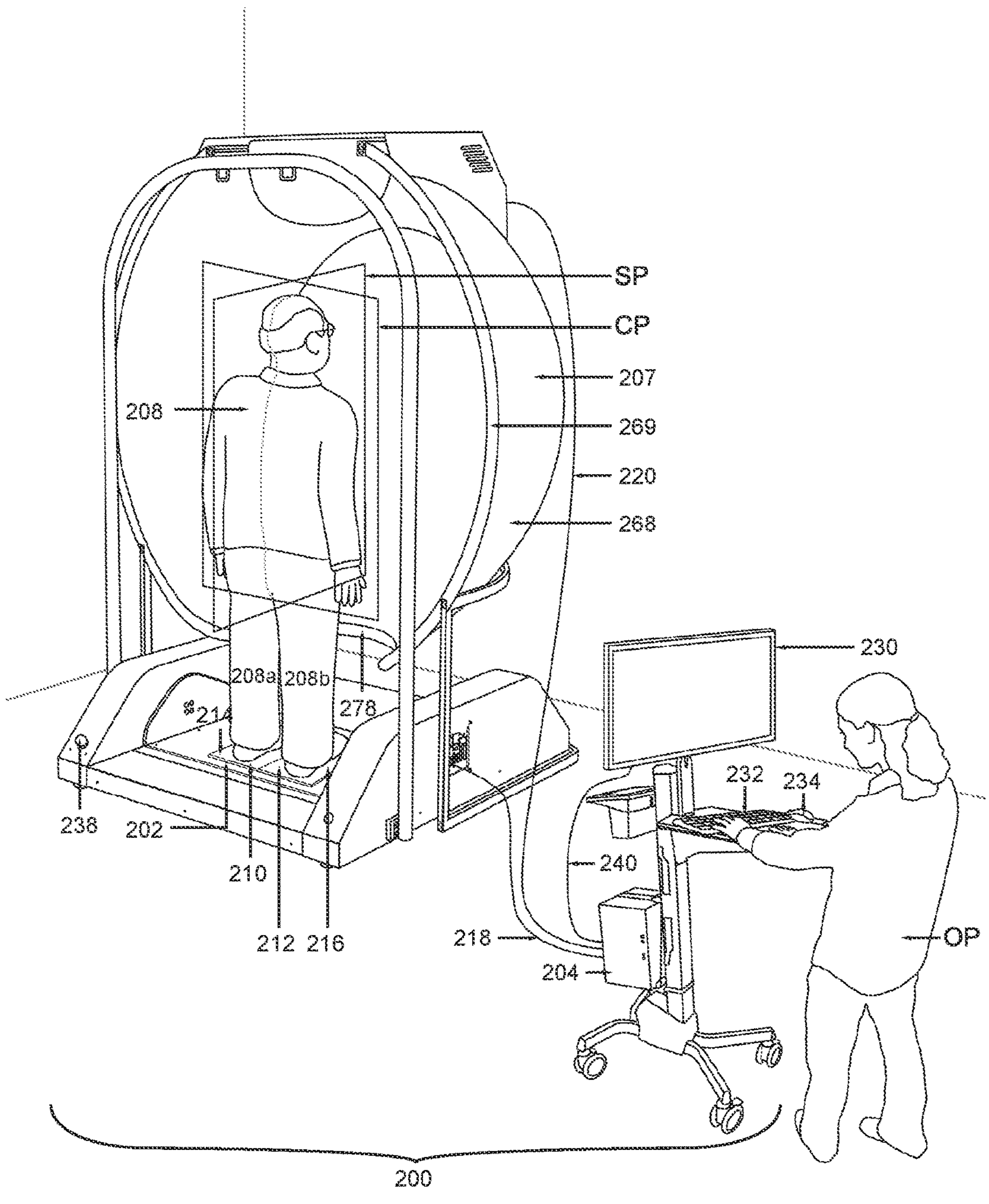

SP
CP
207
208
269
220
268
230
208a
208b
278
214
232
234
238
202
240
210
218
OP
212
216
204
200

FIG. 18

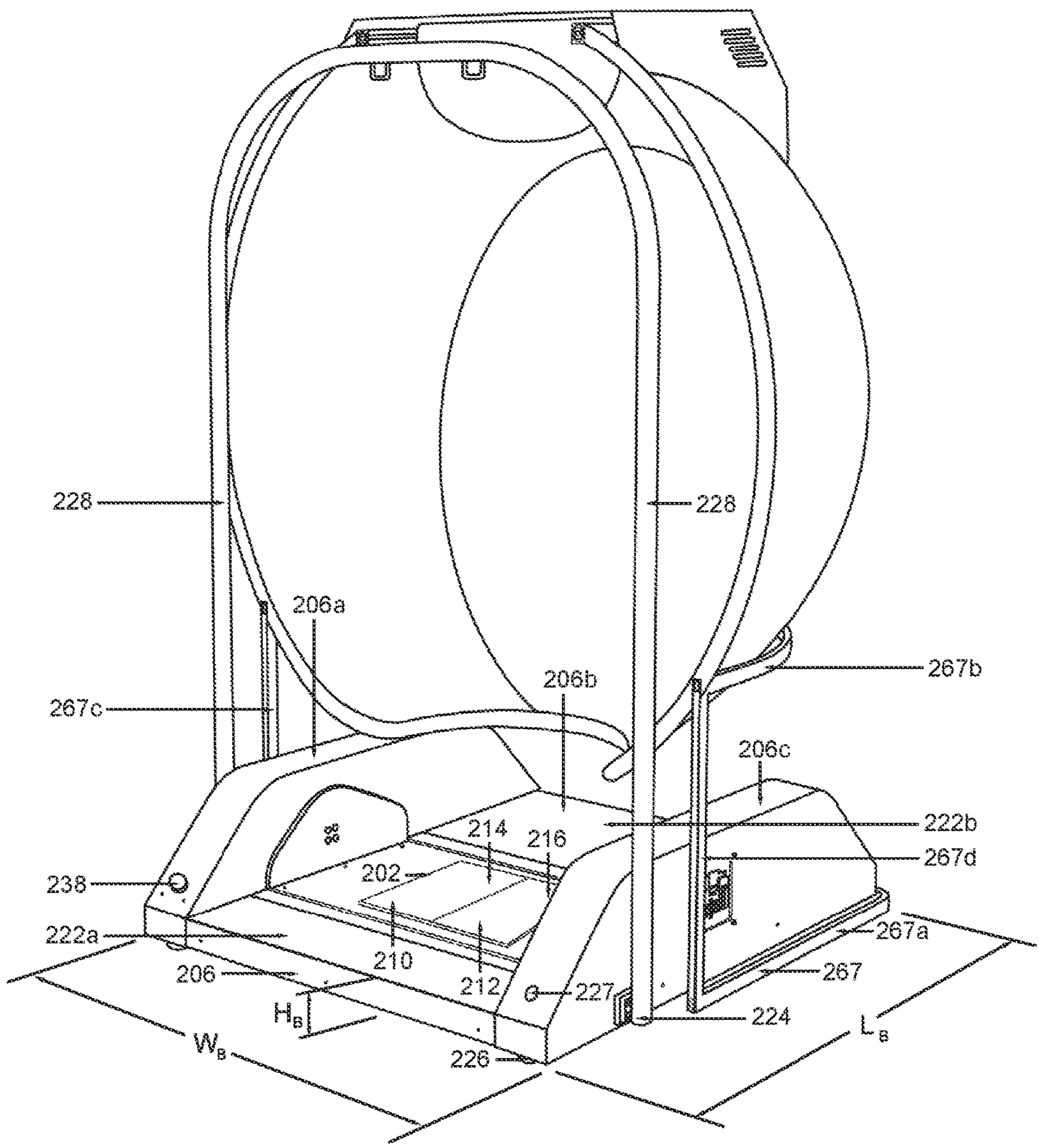

228
228
206a
267c
206b
267b
206c
222b
267d
214
216
238
202
222a
210
267a
206
212
267
227
H_B
224
W_B
226
L_B

FIG. 19

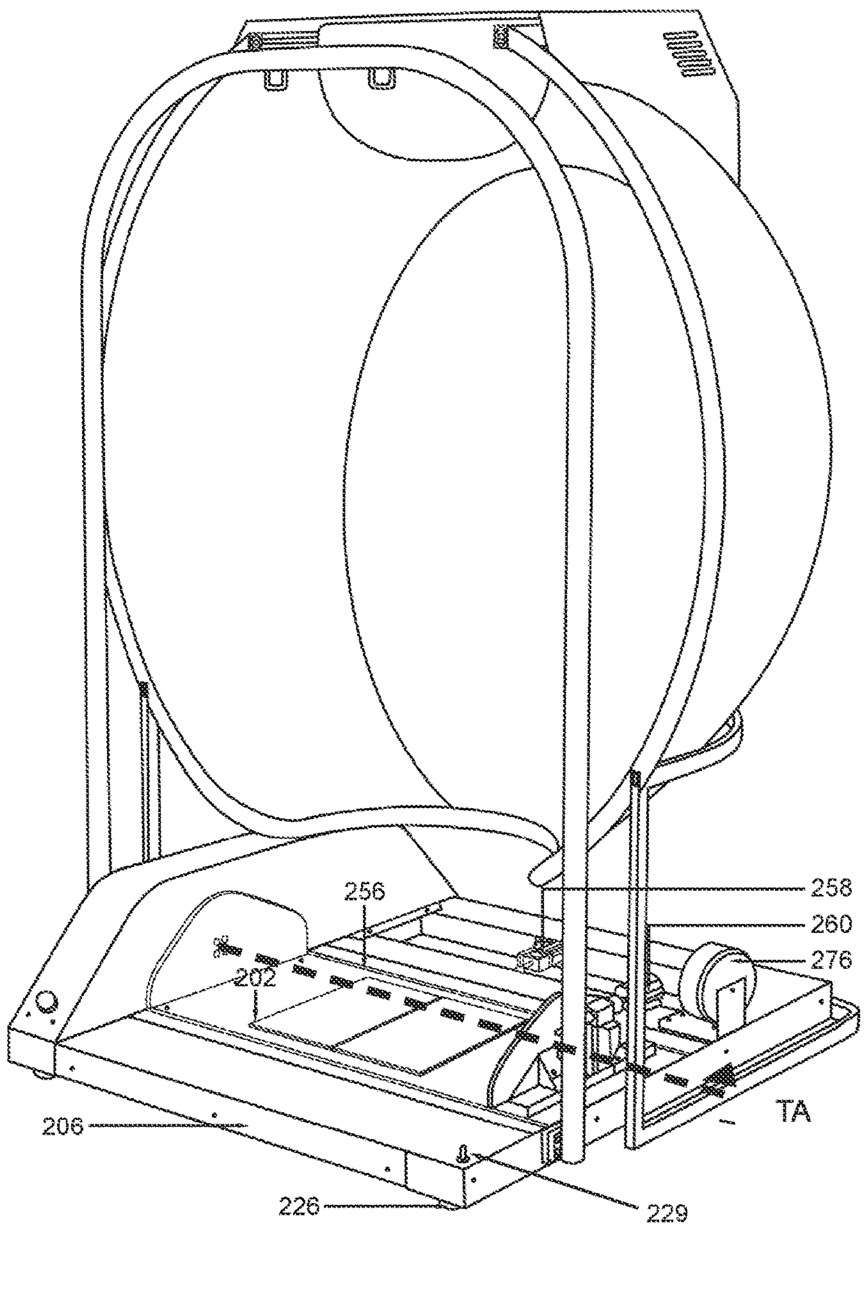
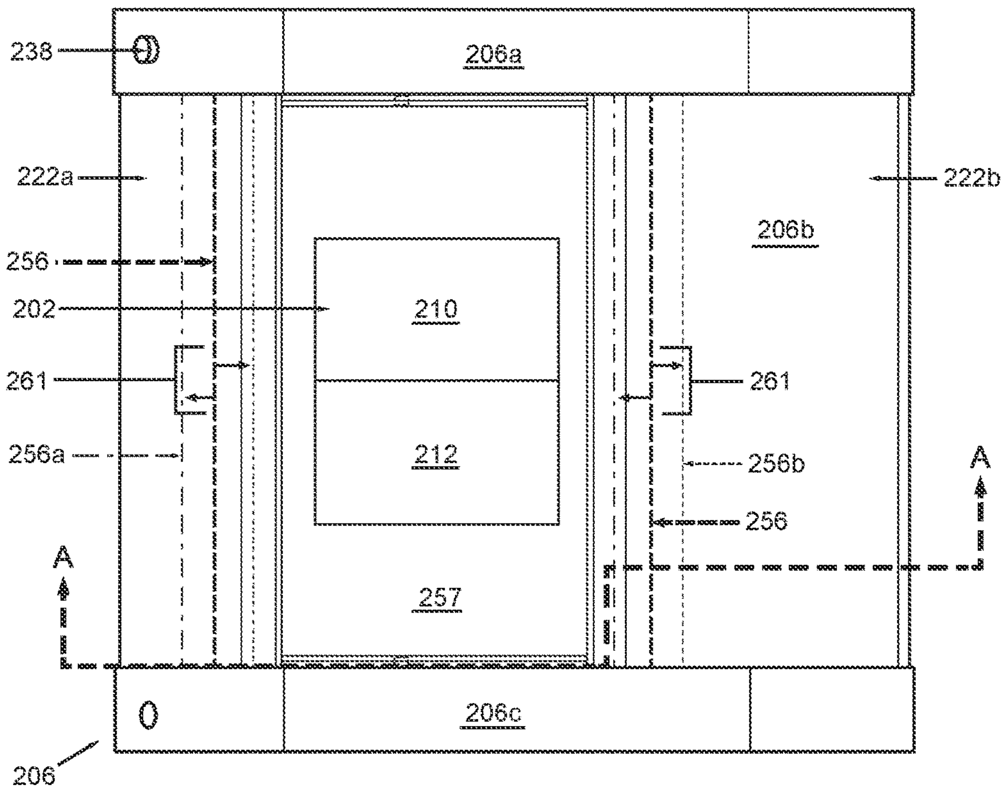
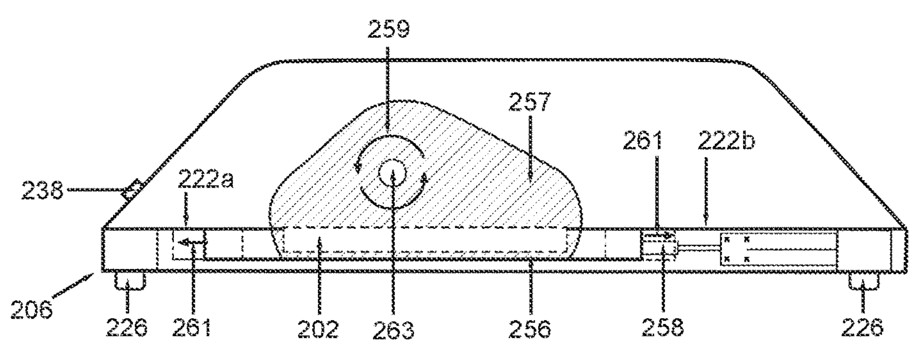


FIG. 20



238
206a
222a
222b
206b
256
202
210
261
261
256a
212
256b
A
256
A
257
0
206c
206

FIG. 21



259
257
261
222b
238
222a
206
226
261
202
263
256
258
226

FIG. 22

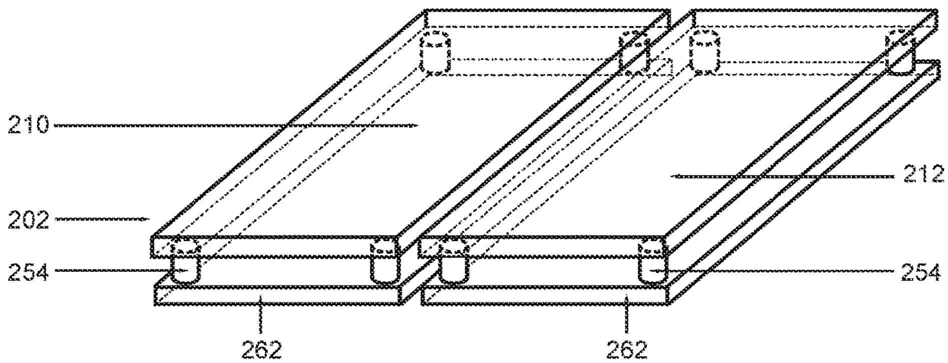

210
212
202
254
254
262
262

FIG. 23

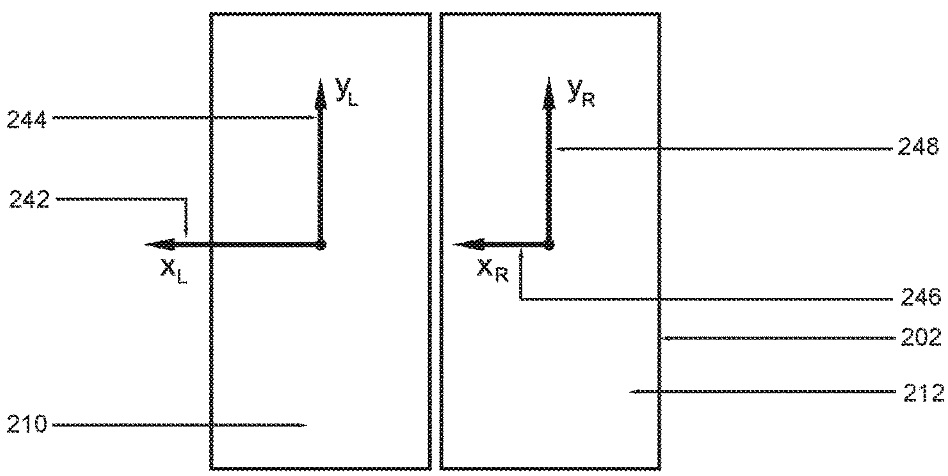
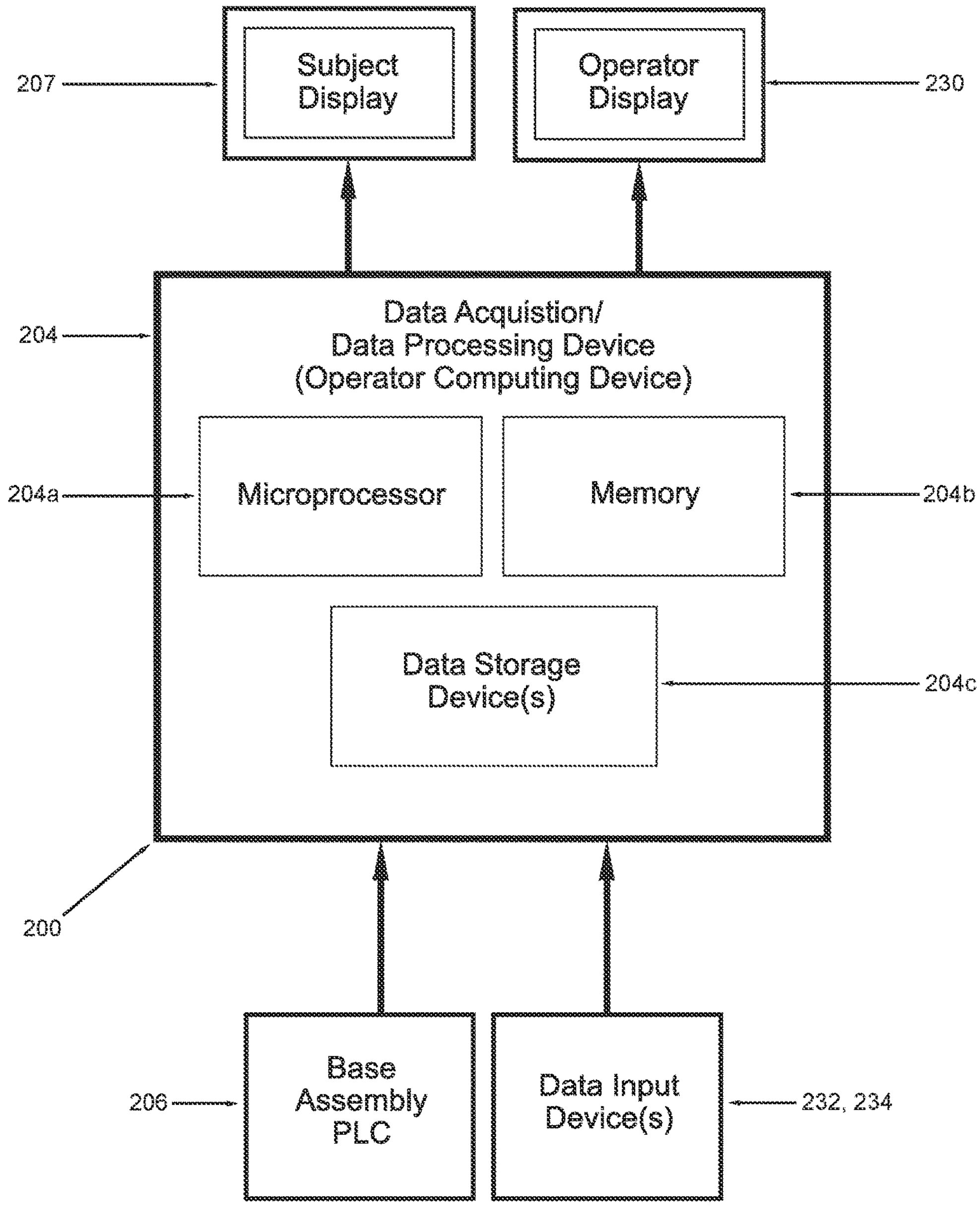
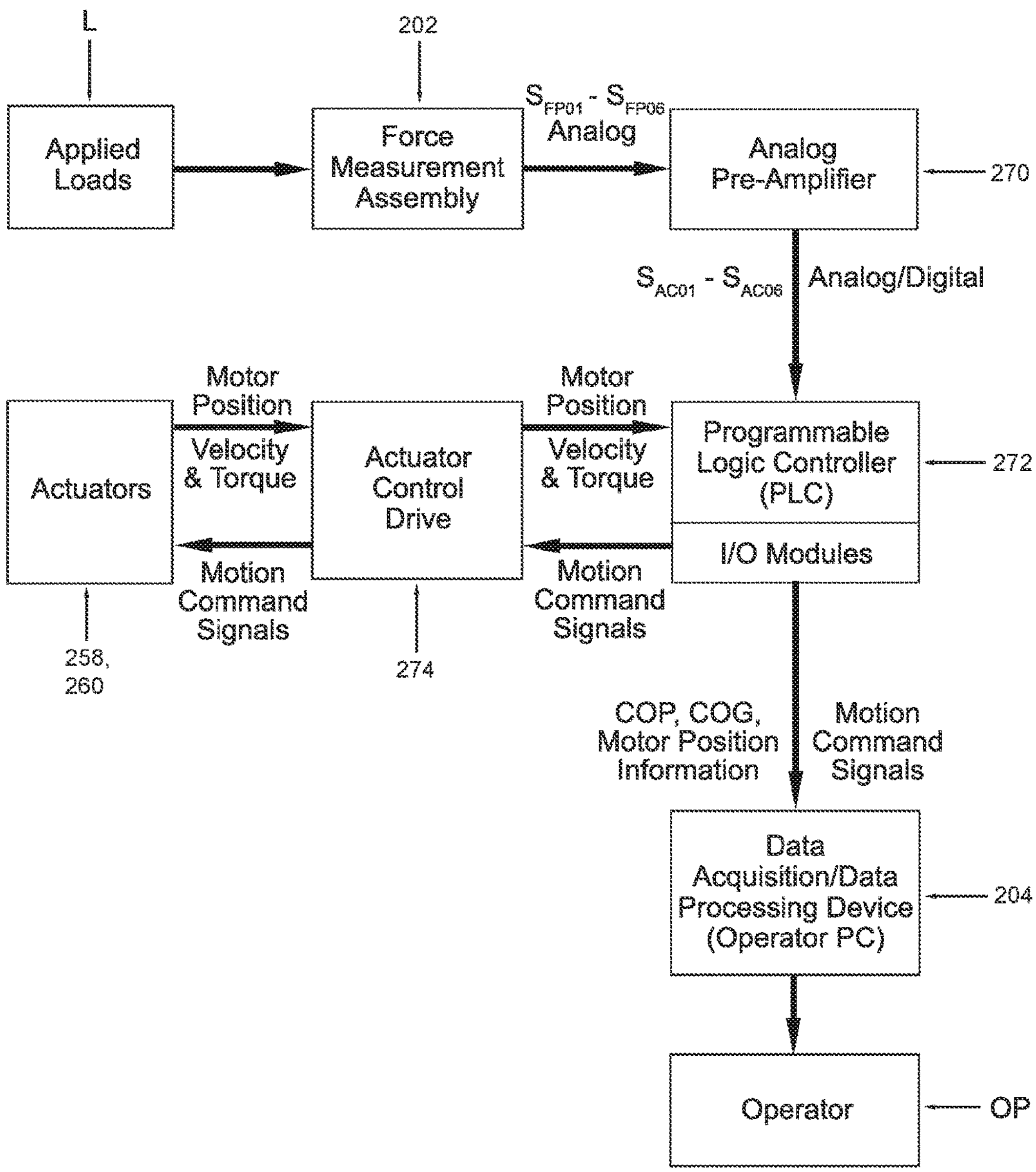

y_L
y_R
244
248
242
x_L
x_R
246
202
212
210

FIG. 24



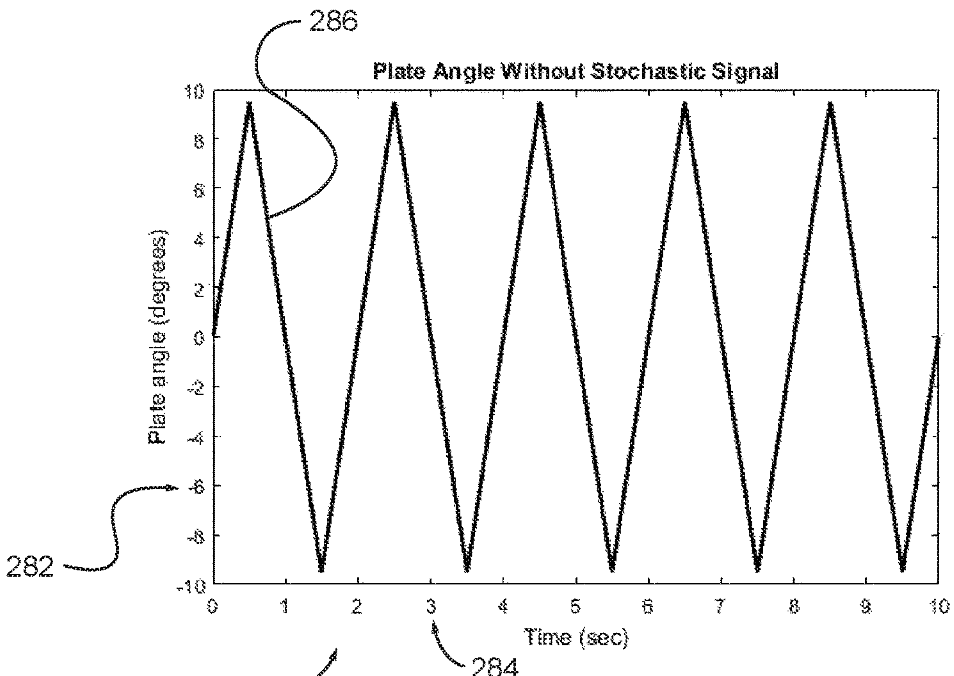
Subject Display
Operator Display
207
230
Data Acquistion/
Data Processing Device
(Operator Computing Device)
204
Microprocessor
Memory
204a
204b
Data Storage Device(s)
204c
200
Base Assembly PLC
Data Input Device(s)
206
232, 234

FIG. 25



L
202
Applied Loads
Force Measurement Assembly
S_{FP01} - S_{FP06}
Analog
Analog Pre-Amplifier
270
S_{AC01} - S_{AC06}
Analog/Digital
Actuators
Motor Position
Velocity & Torque
Actuator Control Drive
Motor Position
Velocity & Torque
Programmable Logic Controller (PLC)
272
I/O Modules
Motion Command Signals
Motion Command Signals
258, 260
274
COP, COG, Motor Position Information
Motion Command Signals
Data Acquisition/Data Processing Device (Operator PC)
204
Operator
OP

FIG. 26



286
Plate Angle Without Stochastic Signal
10
8
6
4
2
0
-2
-4
-6
-8
-10
Plate angle (degrees)
282
0
1
2
3
4
5
6
7
8
9
10
Time (sec)
284
280

FIG. 27

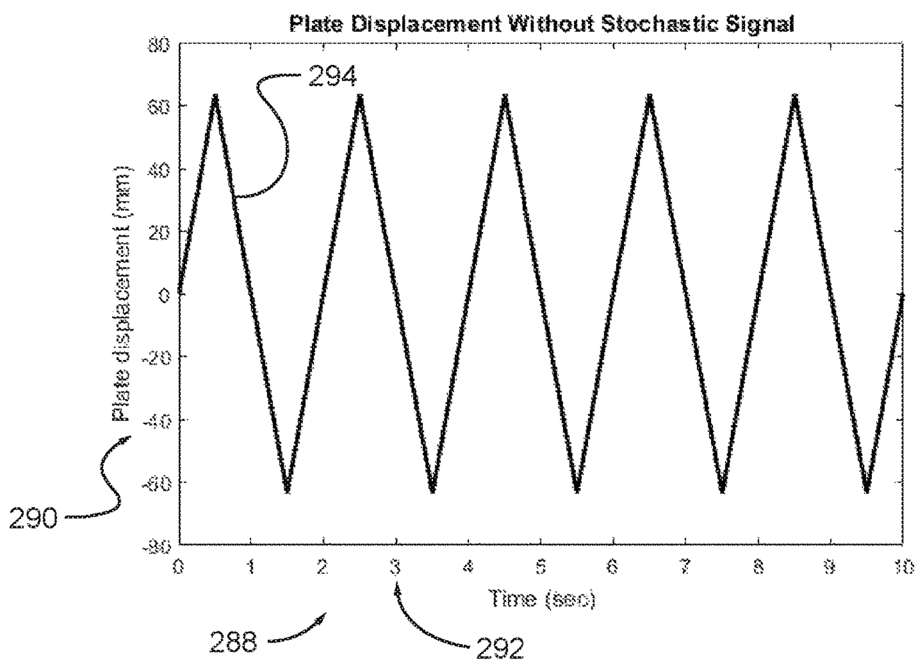


Plate Displacement Without Stochastic Signal
80
60
40
20
0
-20
-40
-60
-80
294
Plate displacement (mm)
290
0
1
2
3
4
5
6
7
8
9
10
Time (sec)
288
292

FIG. 28

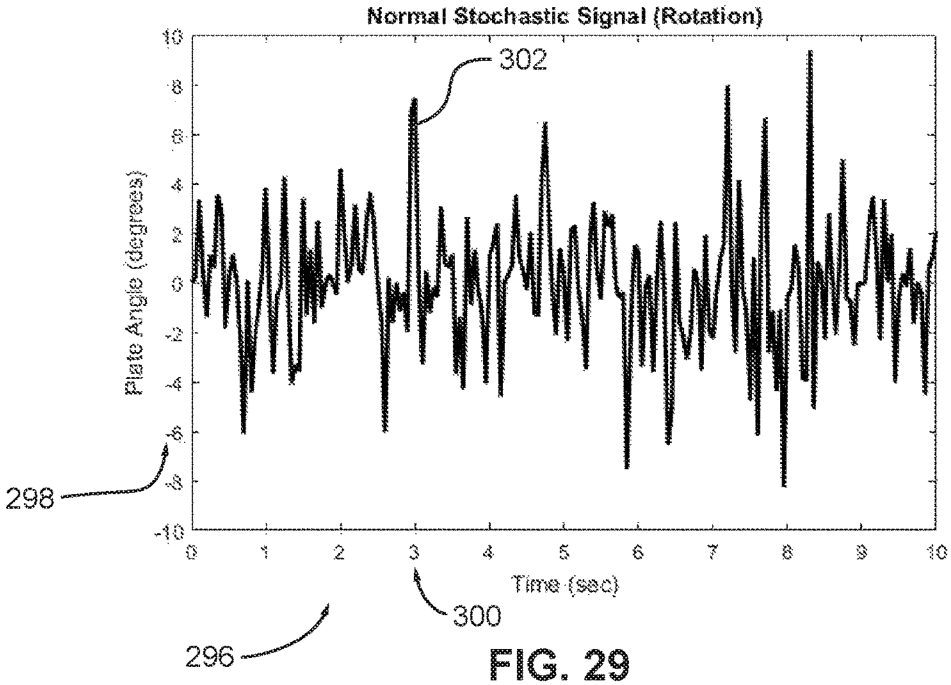

Normal Stochastic Signal (Rotation)
Plate Angle (degrees)
Time (sec)
302
298
300
296

FIG. 29

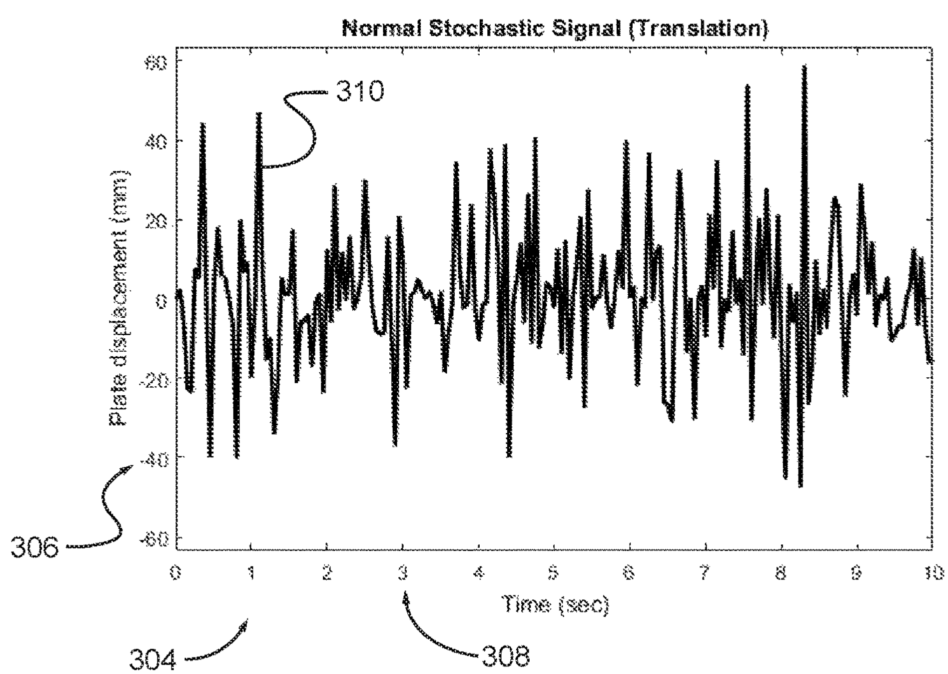
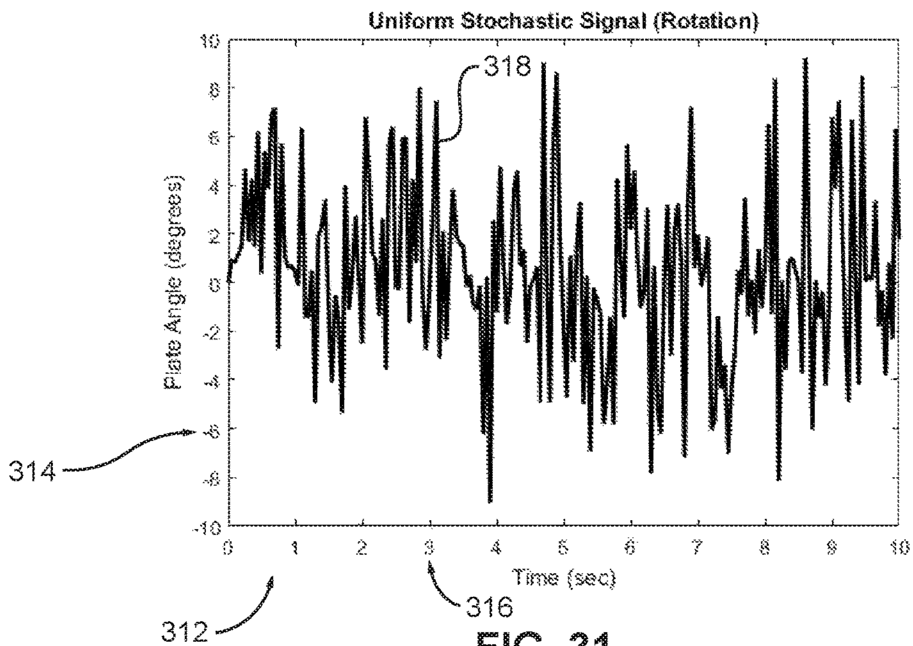
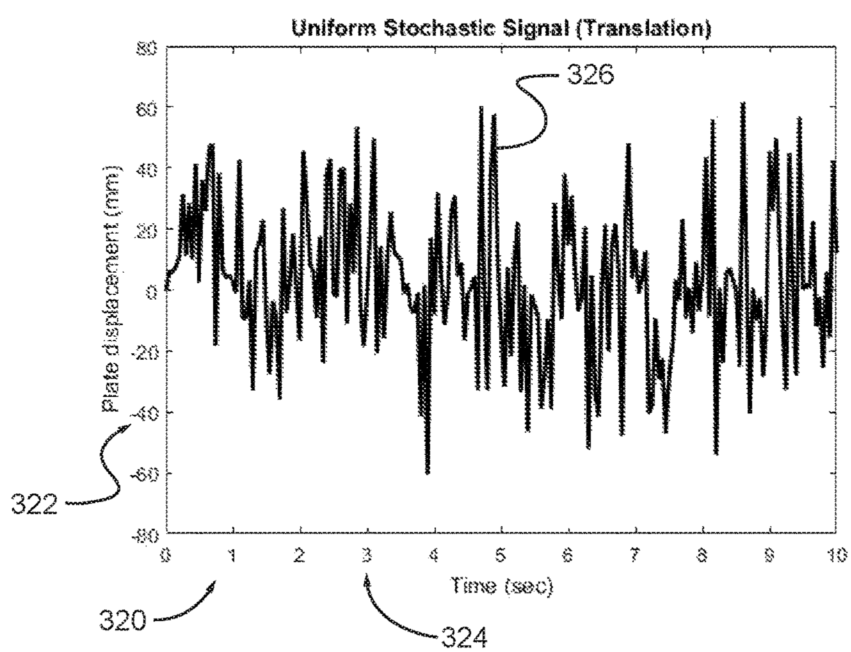

Normal Stochastic Signal (Translation)
Plate displacement (mm)
Time (sec)
310
306
304
308

FIG. 30



Uniform Stochastic Signal (Rotation)
318
Plate Angle (degrees)
Time (sec)
314
312
316

FIG. 31



Uniform Stochastic Signal (Translation)
326
Plate displacement (mm)
Time (sec)
322
320
324

FIG. 32

GAIT PERTURBATION SYSTEM AND A METHOD FOR TESTING AND/OR TRAINING A SUBJECT USING THE SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

This is a continuation-in-part of U.S. Nonprovisional patent application Ser. No. 15/095,040, entitled "Gait Perturbation System and a Method For Testing and/or Training a Subject Using the Same", filed on Apr. 9, 2016, which is incorporated by reference herein in its entirety by this reference thereto.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Not Applicable.

NAMES OF THE PARTIES TO A JOINT RESEARCH AGREEMENT

Not Applicable.

INCORPORATION BY REFERENCE OF MATERIAL SUBMITTED ON A COMPACT DISK

Not Applicable.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention generally relates to a balance and/or gait perturbation system. More particularly, the invention relates to a balance and/or gait perturbation system that is capable of perturbing a balance and/or gait of a person.

2. Background and Description of Related Art

In order to study human motion, subjects are often tested in gait labs which are provided with special equipment disposed therein for measuring body movements, body mechanics, and/or the activity of the muscles (e.g., gait labs with force plates, etc.). The gait analysis performed in the gait lab is typically used to assess, plan, and/or treat subjects with medical conditions affecting their ability to walk. Also, the gait analysis is often used in sports biomechanics to improve athletic performance, and to help identify and/or treat injuries that deleteriously affect athletic performance.

However, the artificial nature of a typical environment for testing and/or training the balance and/or gait of a subject (e.g., a typical gait lab or clinician's office) makes it difficult to simulate the real-life conditions that are encountered by the subject. Also, these artificial environments for balance and gait testing and/or training are unable to effectively simulate the uncertain nature of the stimuli encountered by subjects in real-life scenarios. As such, these artificial balance gait testing and/or training environments are limited in their overall ability to effectively test and/or train subjects for the scenarios that are actually experienced by subjects in the their everyday lives.

Therefore, what is needed is a balance and/or gait perturbation system that is capable of simulating real-life conditions by subjecting the person being tested to static and/or dynamic instability. Moreover, a balance and/or gait perturbation system is needed that is capable of generating random stimuli in order to emulate real-life conditions encountered by the person undergoing testing. Furthermore, what is needed is a balance and/or gait perturbation system that is capable of more effectively training a person with a balance and/or gait disorder by delivering random stimuli to the person so that he or she is able to more effectively react to unpredictable disturbances that are encountered in real-life scenarios.

BRIEF SUMMARY OF EMBODIMENTS OF THE INVENTION

Accordingly, the present invention is directed to a balance and/or gait perturbation system and a method for testing and/or training a subject using the same that substantially obviates one or more problems resulting from the limitations and deficiencies of the related art.

In accordance with one or more embodiments of the present invention, there is provided a balance and/or gait perturbation system comprising a balance and/or gait perturbation device and a data processing device. The balance and/or gait perturbation device is configured to receive a person thereon, and the balance and/or gait perturbation device includes one or more displaceable components configured to be displaced at a plurality of different positions, the one or more displaceable components having one or more surfaces for receiving one or more respective limbs of the person; and one or more first actuators coupled to the one or more displaceable components, the one or more first actuators configured to adjust the displacement position of the one or more displaceable components, the one or more first actuators being primary means for displacing the one or more displaceable components. The data processing device is operatively coupled to the one or more first actuators, the data processing device is configured to generate a stochastic signal for introducing a perturbation to the one or more displaceable components, and the data processing device is further configured to control the displacement position of the one or more displaceable components using the stochastic signal such that the one or more displaceable components perturb a balance and/or gait of the person.

In a further embodiment of the present invention, the balance and/or gait perturbation device comprises a force measurement assembly, and the one or more displaceable components comprise a displaceable force plate subassembly of the force measurement assembly; and the one or more first actuators are configured to adjust the displacement position of the displaceable force plate subassembly.

In yet a further embodiment, the displaceable force plate subassembly includes at least one force transducer, the at least one force transducer configured to sense one or more measured quantities and output one or more measurement signals that are representative of one or more loads being applied to the one or more surfaces of the displaceable force plate subassembly by the person.

In still a further embodiment, the balance and/or gait perturbation device further comprises a base assembly having a stationary portion and a displaceable portion, the displaceable force plate subassembly forming a part of the displaceable portion of the base assembly, the one or more first actuators configured to rotate the displaceable force plate subassembly relative to the stationary portion of the base assembly about a transverse rotational axis disposed above the top surface of the displaceable force plate subassembly.

In yet a further embodiment, the stochastic signal comprises one of: (i) a uniform stochastic signal and (ii) a normal stochastic signal.

In still a further embodiment, the balance and/or gait perturbation system further comprises at least one input device, the at least one input device configured to enable a user to input a perturbation level corresponding to at least of: (i) an amplitude of the stochastic signal, and (ii) a frequency of the stochastic signal; and the data processing device is configured to generate the stochastic signal based upon at least one of: (i) the amplitude of the stochastic signal, and (ii) the frequency of the stochastic signal.

In yet a further embodiment, the stochastic signal comprises a uniform stochastic signal, the data processing device configured to compute the uniform stochastic signal as a function of a randomly generated uniform signal and the perturbation level input by the user.

In still a further embodiment, the stochastic signal comprises a normal stochastic signal, the data processing device configured to compute the normal stochastic signal as a function of a normalized randomly generated uniform signal and the perturbation level input by the user.

In yet a further embodiment, the balance and/or gait perturbation system further comprises secondary means for displacing the one or more displaceable components of the balance and/or gait perturbation device in accordance with a secondary type of displacement that is different from a primary type of displacement of the one or more displaceable components by the one or more first actuators, the secondary means for displacing the one or more displaceable components of the balance and/or gait perturbation device being operatively coupled to the data processing device; and the data processing device is configured to generate a translational perturbation signal and to output the translational perturbation signal to the secondary means for displacing the one or more displaceable components of the balance and/or gait perturbation device so that the one or more displaceable components of the balance and/or gait perturbation device are displaced in accordance with a translational displacement profile.

In still a further embodiment, the secondary means for displacing the one or more displaceable components of the balance and/or gait perturbation device comprise one or more second actuators operatively coupled to the one or more displaceable components.

In accordance with one or more other embodiments of the present invention, there is provided a balance and/or gait perturbation system comprising a balance and/or gait perturbation device and a data processing device. The a balance and/or gait perturbation device is configured to receive a person thereon, the balance and/or gait perturbation device includes one or more displaceable components configured to be displaced at a plurality of different positions, the one or more displaceable components having one or more surfaces for receiving one or more respective limbs of the person; and one or more first actuators coupled to the one or more displaceable components, the one or more first actuators configured to adjust the angular displacement position of the one or more displaceable components; and one or more second actuators coupled to the one or more displaceable components, the one or more second actuators configured to adjust the translational displacement position of the one or more displaceable components. The data processing device is operatively coupled to the one or more first actuators and the one or more second actuators, the data processing device is configured to generate a first perturbation signal for introducing a first type of perturbation to the one or more displaceable components and a second perturbation signal for introducing a second type of perturbation to the one or more displaceable components, and the data processing device is further configured to control the angular displacement position of the one or more displaceable components using the first perturbation signal and the translational displacement position of the one or more displaceable components using the second perturbation signal such that the one or more displaceable components perturb a balance and/or gait of the person.

In a further embodiment of the present invention, the balance and/or gait perturbation device comprises a force measurement assembly, and the one or more displaceable components comprise a displaceable force plate subassembly of the force measurement assembly; and the one or more first actuators are configured to adjust the angular displacement position of the displaceable force plate subassembly; and the one or more second actuators are configured to adjust the translational displacement position of the displaceable force plate subassembly.

In yet a further embodiment, the displaceable force plate subassembly includes at least one force transducer, the at least one force transducer configured to sense one or more measured quantities and output one or more measurement signals that are representative of one or more loads being applied to the one or more surfaces of the displaceable force plate subassembly by the person.

In still a further embodiment, the balance and/or gait perturbation device further comprises a base assembly having a stationary portion and a displaceable portion, the displaceable force plate subassembly forming a part of the displaceable portion of the base assembly, the one or more first actuators configured to rotate the displaceable force plate subassembly relative to the stationary portion of the base assembly about a transverse rotational axis disposed above the top surface of the displaceable force plate subassembly, and the one or more second actuators configured to translate the displaceable force plate subassembly relative to the stationary portion of the base assembly.

In yet a further embodiment, the balance and/or gait perturbation system further comprises at least one input device, the at least one input device configured to enable a user to input a perturbation level corresponding to at least of: (i) an amplitude of the first perturbation signal or the second perturbation signal, and (ii) a frequency of the first perturbation signal or the second perturbation signal; and the data processing device is configured to generate the first perturbation signal or the second perturbation signal based upon at least one of the amplitude or the frequency.

In still a further embodiment, at least one of the first perturbation signal and the second perturbation signal generated by the data processing device comprises a stochastic signal.

In yet a further embodiment, the balance and/or gait perturbation system further comprises at least one input device, the at least one input device configured to enable a user to input a perturbation level corresponding to at least of: (i) an amplitude of the stochastic signal, and (ii) a frequency of the stochastic signal; and the data processing device is configured to generate the stochastic signal based upon at least one of: (i) the amplitude of the stochastic signal, and (ii) the frequency of the stochastic signal.

In accordance with yet one or more other embodiments of the present invention, there is provided a method for testing and/or training a person using a balance and/or gait perturbation system. The method comprising the steps of: (i) providing a balance and/or gait perturbation device configured to receive a person thereon, the balance and/or gait perturbation device including one or more displaceable components configured to be displaced at a plurality of different positions, the one or more displaceable components having one or more surfaces for receiving one or more respective limbs of the person; and one or more first actuators coupled to the one or more displaceable components, the one or more first actuators configured to adjust the displacement position of the one or more displaceable components; (ii) providing a data processing device operatively coupled to the one or more first actuators, the data processing device configured to generate a stochastic signal for introducing a perturbation to the one or more displaceable components, the data processing device further configured to control the displacement position of the one or more displaceable components using the stochastic signal such that the one or more displaceable components perturb a balance and/or gait of the person; (iii) positioning the person on one or more respective surfaces of the one or more displaceable components of the balance and/or gait perturbation device; (iv) generating, by using the data processing device, a stochastic signal for introducing a perturbation to the one or more displaceable components of the balance and/or gait perturbation device; (v) controlling, by using the data processing device, the displacement position of the one or more displaceable components of the balance and/or gait perturbation device using the stochastic signal; and (vi) displacing, by using the one or more first actuators, the one or more displaceable components of the balance and/or gait perturbation device to the displacement position determined using the stochastic signal such that the one or more displaceable components randomly perturb a balance and/or gait of the person.

In a further embodiment of the present invention, the method further comprises the steps of: (vii) providing at least one input device operatively coupled to the data processing device, the at least one input device configured to enable a user to input a perturbation level corresponding to at least of: (a) an amplitude of the stochastic signal, and (b) a frequency of the stochastic signal; and (viii) generating, by using the data processing device, the stochastic signal based upon at least one of: (a) the amplitude of the stochastic signal, and (b) the frequency of the stochastic signal.

In yet a further embodiment, the stochastic signal comprises one of: (a) a uniform stochastic signal and (b) a normal stochastic signal.

It is to be understood that the foregoing general description and the following detailed description of the present invention are merely exemplary and explanatory in nature. As such, the foregoing general description and the following detailed description of the invention should not be construed to limit the scope of the appended claims in any sense.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The invention will now be described, by way of example, with reference to the accompanying drawings, in which:

FIG. **1** is a perspective view of a gait perturbation system with a gait perturbation device in the form of an instrumented treadmill, according to a first embodiment of the invention;

FIG. **2** is an end-side perspective view illustrating the pylon-type force transducers of the instrumented treadmill of FIG. **1**, wherein, in this figure, handrails have been added to the instrumented treadmill of FIG. **1**;

FIG. **3** is a side view illustrating the instrumented treadmill of FIG. **2**;

FIG. **4** is another perspective view of a subject disposed on the instrumented treadmill of FIG. **1**, wherein the subject is outfitted with a plurality of inertial measurement units (IMUs) thereon;

FIG. **5** is a block diagram of constituent components of the gait perturbation system with the instrumented treadmill of FIG. **1**, according to an embodiment of the invention;

FIG. **6** is a block diagram illustrating the electronic actuator components of the instrumented treadmill of FIG. **1**, and the data manipulation operations and motion control operations carried out by the gait perturbation system, according to an embodiment of the invention;

FIG. **7** is a graph illustrating a base velocity signal with no perturbations for controlling the speed set point of the one or more treadmill belts of the instrumented treadmill of FIG. **1**;

FIG. **8** is a graph illustrating a combined base velocity and stochastic signal for controlling the speed set point of the one or more treadmill belts of the instrumented treadmill of FIG. **1**;

FIG. **9** is a graph illustrating a uniform stochastic signal with a base amplitude of 0.9 meters and a cutoff frequency of 5 Hertz;

FIG. **10** is a graph illustrating a uniform stochastic signal with a base amplitude of 0.5 meters and a cutoff frequency of 5 Hertz;

FIG. **11** is a graph illustrating a normal stochastic signal with a base amplitude of 0.9 meters and a cutoff frequency of 5 Hertz;

FIG. **12** is a graph illustrating a uniform stochastic signal with a base amplitude of 0.9 meters and a cutoff frequency of 10 Hertz;

FIG. **13** is a graph illustrating a uniform random numbers curve generated by the data processing device of the gait perturbation system;

FIG. **14** is a graph illustrating a normal random numbers curve generated by the data processing device of the gait perturbation system;

FIG. **15** is a graph illustrating a normal signal curve and filtered data curve at a cut-off frequency of 5 Hertz;

FIG. **16** is a graph illustrating a normal signal curve and filtered data curve at a cut-off frequency of 10 Hertz;

FIG. **17** is a graph comparing filtered data curves with cut-off frequencies of 5 Hertz and 10 Hertz;

FIG. **18** is a perspective view of a balance perturbation system with a balance perturbation device in the form of a displaceable force measurement assembly, according to a second embodiment of the invention;

FIG. **19** is a perspective view of an immersive subject visual display device, a base assembly, and displaceable force measurement assembly of the balance perturbation system of FIG. **18**;

FIG. **20** is a perspective view of an immersive subject visual display device and a cutaway perspective view of a base assembly and displaceable force measurement assembly of the balance perturbation system of FIG. **18**, wherein several covers of the base assembly are removed;

FIG. **21** is a top view of the base assembly illustrated in FIGS. **19** and **20**, according to the second embodiment of the invention;

FIG. **22** is a longitudinal section cut through the base assembly illustrated in FIG. **21**, wherein the section is cut along the cutting plane line A-A in FIG. **21**, according to the second embodiment of the invention;

FIG. **23** is a diagrammatic perspective view of an exemplary force measurement assembly used in the balance perturbation system of FIG. **18**, wherein the force measurement assembly is in the form of a dual force plate;

FIG. **24** is a diagrammatic top view of the force measurement assembly of FIG. **23** used in the balance perturbation system with exemplary coordinate axes superimposed thereon;

FIG. **25** is a block diagram of constituent components of the balance perturbation system having a displaceable force measurement assembly, according to the second embodiment of the invention;

FIG. **26** is a block diagram illustrating data manipulation operations and motion control operations carried out by the balance perturbation system, according to the second embodiment of the invention;

FIG. **27** is a graph illustrating a rotational displacement signal with no perturbations for controlling the angle of the displaceable force measurement assembly of the balance perturbation system in FIG. **18**;

FIG. **28** is a graph illustrating a translational displacement signal with no perturbations for controlling the front-to-back displacement of the displaceable force measurement assembly of the balance perturbation system in FIG. **18**;

FIG. **29** is a graph illustrating a normal stochastic perturbation signal for controlling the angle of the displaceable force measurement assembly of the balance perturbation system in FIG. **18**;

FIG. **30** is a graph illustrating a normal stochastic perturbation signal for controlling the front-to-back displacement of the displaceable force measurement assembly of the balance perturbation system in FIG. **18**;

FIG. **31** is a graph illustrating a uniform stochastic perturbation signal for controlling the angle of the displaceable force measurement assembly of the balance perturbation system in FIG. **18**; and

FIG. **32** is a graph illustrating a uniform stochastic perturbation signal for controlling the front-to-back displacement of the displaceable force measurement assembly of the balance perturbation system in FIG. **18**.

Throughout the figures, the same parts are always denoted using the same reference characters so that, as a general rule, they will only be described once.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

An illustrative embodiment of a gait perturbation system is seen generally at **100** in FIG. **1**. In the first illustrative embodiment of FIG. **1**, the gait perturbation system **100** generally comprises a gait perturbation device **10** in the form of an instrumented treadmill that is operatively coupled to a data acquisition/data processing device **28** (i.e., a data acquisition and processing device or computing device that is capable of collecting, storing, and processing data), which in turn, is operatively coupled to a subject visual display device **52** for displaying images or scenes to the subject **42** disposed on the treadmill **10**. The instrumented treadmill **10** is configured to receive a subject **42** thereon. As best illustrated in FIG. **1**, the instrumented treadmill **10** is attached to the top of a base plate **12**, which in turn, may be secured to a support surface (e.g., a building floor). The instrumented treadmill **10** has a plurality of top surfaces (i.e., left and right rotating belts **14**, **16**) that are each configured to receive a portion of a body of a subject **42** (e.g., the left belt **14** of the instrumented treadmill **10** is configured to receive a left leg of a subject **42**, whereas the right belt **16** of the instrumented treadmill **10** is configured to receive a right leg of the subject **42**).

In one or more embodiments, a subject walks or runs in an upright position atop the treadmill **10** with the feet **42***a*, **42***b* of the subject **42** contacting the respective top surfaces **22**, **24** of the treadmill belts **14**, **16**. The belts **14**, **16** of the treadmill **10** are rotated by independent electric actuator assemblies with one or more speed adjustment mechanisms (e.g., actuator control drive **27** in FIG. **6**). In the illustrated embodiment, each electric actuator assembly comprises an electric motor operatively coupled to the actuator control drive **27**. Under the control of the actuator control drive **27**, each electric actuator assembly is capable of rotating its respective treadmill belt **14**, **16** at a plurality of different speeds. The actuator control drive **27** (i.e., speed adjustment mechanism) adjusts the speed(s) at which each of the treadmill belts **14**, **16** are rotated. The actuator control drive **27** (i.e., speed adjustment mechanism) of the instrumented treadmill **10** is operatively coupled to a programmable logic controller (PLC) **25** (see FIG. **6**). The programmable logic controller **25** of the instrumented treadmill **10** is operatively connected to the data acquisition/data processing device **28** by an electrical cable **26**, while the programmable logic controller **25** is operatively connected to the control portion **18** of the instrumented treadmill **10** (e.g., containing the actuator control drive **27**) via an electrical cable **31** (see FIG. **1**). While they are not readily visible in the perspective view of FIG. **1** due to their location, the instrumented treadmill **10** includes a plurality of force transducers (e.g., four (4) pylon-type force transducers **20**—see e.g., FIGS. **2-4**) disposed below each rotating belt **14**, **16** of the treadmill **10** so that the loads being applied to the top surfaces **22**, **24** of the belts **14**, **16** can be measured. Advantageously, the separated belts **14**, **16** of the instrumented treadmill **10** enable the forces and/or moments applied by the left and right legs of the subject **42** to be independently determined. As will be described in more detail hereinafter, the pylon-type force transducers **20** of the instrumented treadmill **10** are also operatively coupled to the treadmill programmable logic controller **25**. In turn, the treadmill programmable logic controller **25** is operatively coupled to the data acquisition/data processing device **28** so that the force and moment output data of the pylon-type force transducers **20** is capable of being analyzed and processed by the data acquisition/data processing device **28**.

As mentioned above, each of the treadmill belts **14**, **16** is supported atop four (4) pylon-type force transducers **20** (or pylon-type load cells) that are disposed underneath, and near each of the four corners (4) of the left rotating belt **14** of the treadmill **10** and each of the four corners (4) of the right rotating belt **16** (see e.g., FIGS. **2-4**). Each of the eight (8) pylon-type force transducers **20** has a plurality of strain gages adhered to the outer periphery of a cylindrically-shaped force transducer sensing element for detecting the mechanical strain of the force transducer sensing element imparted thereon by the force(s) applied to the belt surfaces **22**, **24** of the instrumented treadmill **10**. In the illustrative embodiment, each of the four (4) sets of pylon-type force transducers **20** are mounted atop the base plate **12**.

In an alternative embodiment, rather than using four (4) pylon-type force transducers **20** on each treadmill belt assembly **14**, **16**, force transducers in the form of transducer beams could be provided under each treadmill belt assembly **14**, **16**. In this alternative embodiment, the left treadmill belt assembly **14** could comprise two transducer beams that are disposed underneath, and on generally opposite sides of the treadmill belt assembly **14**. Similarly, in this embodiment, the right treadmill belt assembly **16** could comprise two transducer beams that are disposed underneath, and on generally opposite sides of the right treadmill belt assembly **16**. Similar to the pylon-type force transducers **20**, the force transducer beams could have a plurality of strain gages attached to one or more surfaces thereof for sensing the mechanical strain imparted on the beam by the force(s) applied to the surfaces **22**, **24** of the instrumented treadmill **10**.

Rather, than using four (4) force transducer pylons under each treadmill belt assembly **14**, **16**, or two spaced-apart force transducer beams under each treadmill belt assembly **14**, **16**, it is to be understood that the instrumented treadmill **10** can also utilize the force transducer technology described in U.S. Pat. No. 8,544,347, the entire disclosure of which is incorporated herein by reference.

In the illustrated embodiment, the electrical cable **26** mentioned above is used for the transmission of data between the programmable logic controller **25** and the data acquisition/data processing device **28**, while the electrical cable **31** is used for the transmission of data between the instrumented treadmill **10** and the programmable logic controller **25**. A separate power cable is used to provide power to the instrumented treadmill **10** (e.g., a power cable connected directly to the electrical power system of the building in which the treadmill **10** is disposed). While a hardwired data connection is provided between the programmable logic controller **25** and the data acquisition/data processing device **28** in the illustrative embodiment, it is to be understood that the programmable logic controller **25** can be operatively coupled to the data acquisition/data processing device **28** using other signal transmission means, such as a wireless data transmission system.

Now, turning to FIG. **5**, it can be seen that the illustrated data acquisition/data processing device **28** (i.e., the operator computing device) of the gait perturbation system **100** includes a microprocessor **28***a* for processing data, memory **28***b* (e.g., random access memory or RAM) for storing data during the processing thereof, and data storage device(s) **28***c*, such as one or more hard drives, compact disk drives, floppy disk drives, flash drives, or any combination thereof. As shown in FIG. **1**, the programmable logic controller (PLC) **25** of the instrumented treadmill **10**, and the subject visual display device **52** are operatively coupled to the data acquisition/data processing device **28** such that data is capable of being transferred between these devices **25**, **28**, and **52**. In FIG. **1**, it can be seen that the programmable logic controller (PLC) **25** of the instrumented treadmill **10** is operatively coupled to the data acquisition/data processing device **28** by the electrical cable **26**, while the subject visual display device **52** is operatively coupled to the data acquisition/data processing device **28** by the electrical cable **54**. Also, as shown in FIG. **1**, the data acquisition/data processing device **28** (e.g., in the form of a laptop digital computer) generally includes a base portion **30** with the microprocessor **28***a* disposed therein for collecting and processing the data that is received from the instrumented treadmill **10**, and a plurality of devices **32-36** operatively coupled to the microprocessor **28***a* in the base portion **30**. Preferably, the devices that are operatively coupled to the microprocessor **28***a* of the data acquisition/data processing device **28** comprise user input devices **32**, **36** in the form of a keyboard **32** and a touchpad **36**, as well as a graphical user interface in the form of a laptop LCD screen **34**. While a laptop type computing system is depicted in FIG. **1**, one of ordinary skill in the art will appreciate that another type of data acquisition/data processing device **28** can be substituted for the laptop computing system such as, but not limited to, a palmtop computing device (i.e., a PDA) or a desktop type computing system having a plurality of separate, operatively coupled components (e.g., a desktop type computing system including a main housing with a central processing unit (CPU) and data storage devices, a remote monitor, a remote keyboard, and a remote mouse). In addition, rather than providing a data acquisition/data processing device **28**, it is to be understood that, in other embodiments, only a data acquisition device could be provided without departing from the spirit and the scope of the claimed invention.

Advantageously, the programmable logic controller **25** (see e.g., FIG. **6**, which is a type of data processing device) provides real-time control of the treadmill actuators (i.e., motors) that control the rotation of the left and right treadmill belts **14**, **16**. The real-time control provided by the programmable logic controller **25** ensures that the software regulating the control of the left and right treadmill belts **14**, **16** operates at the design clock rate, thereby providing fail-safe operation for subject safety. As such, user software applications that are being executed on the data acquisition/data processing device **28** do not interfere with the control of the left and right treadmill belts **14**, **16**. In one embodiment, the programmable logic controller **25** comprises both the treadmill control software and the input/output management software, which controls the functionality of the input/output (I/O) module of the programmable logic controller **25**. In one embodiment, the programmable logic controller **25** utilizes EtherCAT protocol for enhanced speed capabilities and real-time control.

In one or more embodiments, the input/output (I/O) module of the programmable logic controller **25** allows various accessories to be added to the force measurement system **100**. For example, an eye movement tracking system, such as that described by U.S. Pat. Nos. 6,113,237 and 6,152,564 could be operatively connected to the input/output (I/O) module of the programmable logic controller **25**. As another example, a head movement tracking system, which is instrumented with one or more accelerometers, could be operatively connected to the input/output (I/O) module.

FIG. **6** graphically illustrates the acquisition and processing of the load data and the control of the actuators **29** carried out by the exemplary gait perturbation system **100**. Initially, as shown in FIG. **6**, a load L is applied to the treadmill force measurement assembly **21** by a subject disposed thereon. In the illustrative embodiment, the force measurement assembly **21** of the gait perturbation system **100** comprises the pylon-type force transducers **20** disposed underneath the treadmill belts **14**, **16** described above. The load is transmitted from the treadmill belt assemblies **14**, **16** to its respective set of pylon-type force transducers **20** (or force transducer beams). As described above, in the illustrated embodiment, each treadmill belt assembly **14**, **16** comprises four (4) pylon-type force transducers **20** disposed thereunder. Preferably, these pylon-type force transducers **20** are disposed near respective corners of each treadmill belt assembly **14**, **16**. In a preferred embodiment, each of the pylon-type force transducers **20** includes a plurality of strain gages wired in one or more Wheatstone bridge configurations, wherein the electrical resistance of each strain gage is altered when the associated portion of the associated pylon-type force transducer undergoes deformation resulting from the load (i.e., forces and/or moments) acting on the treadmill belt assemblies **14**, **16**. For each plurality of strain gages disposed on the pylon-type force transducers **20**, the change in the electrical resistance of the strain gages brings about a consequential change in the output voltage of the Wheatstone bridge (i.e., a quantity representative of the load being applied to the measurement surface). In one embodiment, the four (4) pylon-type force transducers **20** disposed under the treadmill belt assemblies **14**, **16** output a total of twelve (12) output voltages (signals) in either analog or digital form. In some embodiments, if the output voltages (signals) are in analog form, the twelve (12) output voltages (signals) from the treadmill belt assemblies **14**, **16** are then transmitted to a preamplifier board **23** for preconditioning. The preamplifier board **23** is used to increase the magnitudes of the transducer analog voltages. After which, in one or more embodiments, the analog output signals S_{ACO1}-S_{AC12} are transmitted from the analog preamplifier **23** to the treadmill programmable logic controller (PLC) **25**. In the treadmill programmable logic controller **25**, the analog output signals S_{ACO1}-S_{AC12} may be converted into forces, moments, centers of pressure (COP), subject center of gravity (COG), and/or sway angle for the subject. Then, the forces, moments, centers of pressure (COP), subject center of gravity (COG) **44** (see FIG. **1**), and/or sway angle for the subject **42** computed by the programmable logic controller **25** are transmitted to the data acquisition/data processing device **28** (operator computing device **28**) so that they can be utilized for analyzing the movement of the subject **42** and/or for reports displayed to an operator or clinician. Also, in yet another embodiment, the preamplifier board additionally could be used to convert the analog voltage signals into digital voltage signals (i.e., the preamplifier board could be provided with an analog-to-digital converter). In this embodiment, digital voltage signals would be transmitted to the treadmill programmable logic controller **25** rather than analog voltage signals.

In one or more embodiments, as shown in FIG. **6**, when the programmable logic controller **25** receives the voltage signals S_{ACO1}-S_{AC12}, it initially transforms the signals into output forces and/or moments by multiplying the voltage signals S_{ACO1}-S_{AC12} by a calibration matrix. After which, the force and moment components (i.e., F_{Lx}, F_{Ly}, F_{Lz}, M_{Lx}, M_{Ly}, M_{Lz}) exerted on the left belt surface **22** of the left treadmill belt assembly **14** by the left foot of the subject, the force and moment components (i.e., F_{Rx}, F_{Ry}, F_{Rz}, M_{Rx}, M_{Ry}, M_{Rz}) exerted on the right belt surface **24** of the right treadmill belt assembly **16** by the right foot of the subject, and the center of pressure (x_{P_L}, y_{P_L}; x_{P_R}, y_{P_R}) for each foot of the subject (i.e., the x and y coordinates of the point of application of the force applied to the measurement surface by each foot) are determined by the programmable logic controller **25**, and then transmitted to the data acquisition/data processing device **28**.

In one or more alternative embodiments, as also shown in FIG. **6**, the voltage signals S_{ACO1}-S_{AC12} may be transmitted to the data acquisition/data processing device **28**, rather than to the programmable logic controller **25**. In these one or more alternative embodiments, when the data acquisition/data processing device **28** receives the signals S_{ACO1}-S_{AC12}, it initially transforms the signals S_{ACO1}-S_{AC12} into output forces and/or moments by multiplying the voltage signals S_{ACO1}-S_{AC12} by the calibration matrix. After which, the force and moment components (i.e., F_{Lx}, F_{Ly}, F_{Lz}, M_{Lx}, M_{Ly}, M_{Lz}) exerted on the left belt surface **22** of the left treadmill belt assembly **14** by the left foot of the subject, the force and moment components (i.e., F_{Rx}, F_{Ry}, F_{Rz}, M_{Rx}, M_{Ry}, M_{Rz}) exerted on the right belt surface **24** of the right treadmill belt assembly **16** by the right foot of the subject, and the center of pressure (x_{P_L}, y_{P_L}; x_{P_R}, y_{P_R}) for each foot of the subject (i.e., the x and y coordinates of the point of application of the force applied to the measurement surface by each foot) are determined by the data acquisition/data processing device **28**.

Also, in one or more embodiments, as shown in the perspective view of FIG. **1**, the overall center of pressure (x_P, y_P) may also be determined for the subject **42** in accordance with the overall x-coordinate axis **58** and overall y-coordinate axis **56** disposed on the surface of the instrumented treadmill **10**.

In the illustrated embodiment, the programmable logic controller **25** converts the computed center of pressure (COP) to a center of gravity (COG) for the subject using a Butterworth filter. For example, in one exemplary, non-limiting embodiment, a second-order Butterworth filter with a 0.75 Hz cutoff frequency is used. In addition, the programmable logic controller **25** also computes a sway angle for the subject using a corrected center of gravity (COG') value, wherein the center of gravity (COG) value is corrected to accommodate for the offset position of the subject relative to the origin of the coordinate axes (**56**, **58**) of the treadmill force measurement assembly **21**. For example, the programmable logic controller **25** computes the sway angle for the subject in the following manner:

$$\theta = \sin^{-1}\left(\frac{COG'}{0.55h}\right) - 2.3^\circ \tag{1}$$

where:

θ: sway angle of the subject;

COG': corrected center of gravity of the subject; and

h: height of the center of gravity of the subject.

Now, referring again to the block diagram of FIG. **6**, the manner in which the perturbations of the instrumented treadmill **10** are controlled will be explained. Initially, an operator OP inputs one or more motion commands (e.g., start/stop of treadmill belts **14**, **16**) and/or stochastic signal parameters (e.g., stochastic signal type, amplitude, and cutoff frequency) at the operator computing device **28** (data acquisition/data processing device **28**) by utilizing one of the user input devices **32**, **36**. Once, the one or more motion commands and/or stochastic signal parameters are received at the operator computing device **28**, the one or more motion commands and/or stochastic signal parameters are transmitted to the programmable logic controller **25**. Then, after further processing by the programmable logic controller **25**, the motion command signals (e.g., the one or more base velocity and stochastic signals including the stochastic velocity, stochastic angles, and stochastic amplitude) are transmitted to the actuator control drive **27**. Alternatively, when the data acquisition/data processing device **28** generates the stochastic signal rather than the programmable logic controller **25**, the motion command signals (e.g., the one or more base velocity and stochastic signals including the stochastic velocity, stochastic angles, and stochastic amplitude) are transmitted from the data acquisition/data processing device **28** directly to the actuator control drive **27**, rather than to the programmable logic controller **25**. Finally, the actuator control drive **27** transmits the direct-current (DC) motion command signals to the actuators **29** so that the treadmill belts **14**, **16**, and the subject **42** disposed thereon, can be displaced in the desired manner. The actuator control drive **27** controls the position, velocity, and torque of each actuator motor. Also, as shown in FIG. **6**, the motion command signals sent from the actuator control drive **27** to the treadmill actuators **29** may include any one or all of the following: (i) the stochastic belt speed(s), (ii) stochastic angles in three (3) axes, and (iii) stochastic translations in front-to-back and side-to-side directions. In the illustrative embodiment, each of the treadmill belts **14**, **16** may be provided with a dedicated rotational actuator **29** for the controlling the belt speeds thereof. In addition, the instrumented treadmill **10** may be provided with three (3) or more actuators **29** for rotating the instrumented treadmill **10** about the x, y, and z-coordinate axes, one or more translational actuators **29** for displacing the instrumented treadmill **10** in a front-to-back direction, and one or more translational actuators **29** for displacing the instrumented treadmill **10** in a side-to-side direction (i.e., secondary means for displacing the one or more displaceable components of the gait perturbation device in a side-to-side direction different from the primary front-to-back direction of the displacement of the belts **14**, **16**). Referring again to FIG. **6**, in the alternative embodiment, it can be seen that the stochastic velocity, stochastic angles, and the stochastic amplitude may be transmitted directly from the operator computing device **28** to the actuator control drive **27** for controlling the actuators **29**. The actuators **29** for rotating the instrumented treadmill **10** about the x, y, and z-coordinate axes, and for translating the treadmill **10**, may be incorporated in a motion base disposed underneath the instrumented treadmill **10**, such as that illustrated and described in commonly owned U.S. Pat. No. 9,081,436, the entire disclosure of which is incorporated herein by reference.

In order to accurately control the motion of the instrumented treadmill **10**, a closed-loop feedback control routine may be utilized by the gait perturbation system **100**. As shown in FIG. **6**, the actuator control drive **27** receives the position, velocity, and torque of each actuator motor from the encoders provided as part of each actuator assembly **29**. Then, from the actuator control drive **27**, the position, velocity, and torque of each actuator motor is transmitted to the programmable logic controller **25**, wherein the feedback control of the actuator assemblies **29** is carried out. In addition, the position, velocity, and torque of each actuator motor may also be transmitted from the actuator control drive **27** to the operator computing device **28** so that it is capable of being used to characterize the movement of the subject **42** on the instrumented treadmill **10** (e.g., the motor positional data and/or torque can be used to compute the sway of the subject).

In one or more embodiments, an emergency stop switch may be operatively coupled to the programmable logic controller **25** in order to quasi-instantaneously stop the rotation of the treadmill belts **14**, **16** and/or the displacement of the instrumented treadmill **10** by the actuators **29**. As such, the emergency stop switch is a safety mechanism that protects a subject disposed on the instrumented treadmill **10** from potential injury. In an exemplary embodiment, the emergency stop switch may be in the form of a red push-button that can be easily pressed by a user of the gait perturbation system **100** in order to stop the rotation of the treadmill belts **14**, **16**.

Turning to FIGS. **2** and **3**, it can be seen that the instrumented treadmill **10'** is similar in all respects to the instrumented treadmill **10** of FIGS. **1** and **4**, except that the instrumented treadmill **10'** in FIGS. **2** and **3** further includes handrails **46** attached to the base plate **12**. While the subject **42** is walking or running on the instrumented treadmill **10'**, the handrails **46** can be grasped by the subject **42** in the event that the subject **42** loses his or her balance on the treadmill. Also, the subject **42** may grasp the handrails **46** when he or she first begins walking or running on the treadmill **10'**. In addition, subjects who have balance and mobility problems may use the handrails **46** to stabilize themselves while walking or running on the treadmill **10'**.

In one or more further embodiments, the gait perturbation system **100** that includes the instrumented treadmill **10** and the data acquisition/data processing device **28** further includes a body position measurement system **60** (refer to diagrammatic representation of the system in FIG. **5**). The body position measurement system **60** is configured to detect the position of an upper body portion of the subject and output one or more position data signals that are representative of the position of the upper body portion of the subject. In one or more embodiments, the upper body portion of the subject is disposed above the feet of the subject. In particular, with reference to FIG. **1**, the body position measurement system **60** may comprise a motion capture system having a plurality of cameras **38**. In another embodiment, as shown in FIG. **4**, the body position measurement system **60** may comprises a plurality of inertial measurement units (IMUs) **48** configured to be coupled to the upper body portion of the subject (e.g., as described below with regard to FIG. **4**). It is to be understood that the system **100** may comprise any number or all of these body position measurement systems **38**, **48** depending on the type(s) of measurements that need to be performed by the system **100**.

As shown in the illustrative embodiment of FIG. **1**, when the body position measurement system **60** of the gait perturbation system **100** is in the form of a motion capture system, a plurality of cameras **38** are disposed around the instrumented treadmill **10** so that the cameras **38** at least partially surround the subject **42** disposed on the treadmill **10**. In the illustrative embodiment, the cameras **38** are used to track positions of a plurality of markers **40** disposed on the subject **42** as the subject moves his or her torso and limbs in 3-dimensional space. The markers on the subject **42** are used to record the position of the torso and limbs of the subject **42** in 3-dimensional space. While ten (10) cameras **38** are depicted in FIG. **1**, one of ordinary skill in the art will appreciate that more or less cameras can be utilized, provided that the motion of the subject **42** is capable of being captured from substantially all angles. In the illustrative embodiment of the invention, the subject **42** has a plurality of single markers **40** applied to anatomical landmarks (e.g., the iliac spines of the pelvis, the malleoli of the ankle, and the condyles of the knee), and/or clusters of markers applied to the middle of body segments. As the subject **42** executes particular movements on the instrumented treadmill **10**, the data acquisition/data processing device **28** is specially programmed to calculate the trajectory of each marker **40** in three (3) dimensions. Then, once the positional data is obtained using the motion capture system of FIG. **1**, inverse kinematics may be employed in order to further determine the joint angles of the subject **42**. That is, the motion capture system of FIG. **1** generates motion capture data that is representative of the captured motion of the body portions of the subject, and the data acquisition/data processing device **28** is specially programmed to determine the position of the body of the subject (i.e., limbs, torso, head, etc.) and the joint angles of the subject from the motion capture data generated by the motion capture system.

While the motion capture system of FIG. **1** described above employs a plurality of markers **40**, it is to be understood that the invention is not so limited. Rather, in another embodiment of the invention, a markerless motion detection/motion capture system is utilized. The markerless motion capture system uses a plurality of high speed video cameras to record the motion of a subject without requiring any markers to be placed on the subject. Both of the aforementioned marker and markerless motion detection/motion capture systems are optical-based systems. In one embodiment, the optical motion capture system utilizes visible light, while in another alternative embodiment, the optical motion capture system employs infrared light (e.g., the system could utilize an infrared (IR) emitter to project a plurality of dots onto objects in a particular space as part of a markerless motion capture system). For example, in one or more embodiments, the optical motion capture system may comprise a motion capture device with one or more cameras, one or more infrared (IR) depth sensors, and one or more microphones, which may be used to provide full-body three-dimensional (3D) motion capture, facial recognition, and voice recognition capabilities. It is also to be understood that, rather than using an optical motion detection/capture system, a suitable magnetic or electro-mechanical motion detection/capture system may also be employed to determine the position of the subject **42** on the instrumented treadmill **10**.

In the illustrative embodiment, the cameras **38** depicted in FIG. **1** may be in the form of infrared-type (IR) or near infrared-type (NIR) cameras having an angular field of view range between approximately 40 degrees and approximately 80 degrees (or between 40 degrees and 80 degrees). More particularly, in one or more embodiments, the angular field of view range of the cameras **38** may be between approximately 50 degrees and approximately 70 degrees (or between 50 degrees and 70 degrees). Also, in one or more exemplary embodiments, the cameras **38** depicted in FIG. **1** may have a resolution of approximately 1.0 Megapixels, a maximum frame rate of approximately 250 feet per second (fps), and a 4 millimeter to 12 millimeter (4-12 mm) zoom lens. The cameras **38** are positioned in the gait perturbation system **100** of FIG. **1** so that each marker disposed on a subject **42** standing on the instrumented treadmill **10** is captured by at least two (2) of the cameras **38**, and preferably, three (3) of the cameras **38**.

Now, referring to FIG. **4**, another manner in which the data acquisition/data processing device **28** may determine a position of a body portion (e.g., torso, pelvis, or head) of the subject **42** will be described. In particular, the data acquisition/data processing device **28** may also determine the position of the body portion of the subject **42** by utilizing the inertial measurement units (IMUs) **48** illustrated in FIG. **4**. As shown in this figure, a subject **42** may be outfitted with a plurality of different inertial measurement units **48** for detecting motion. In the illustrative embodiment, the subject **42** is provided with two (2) inertial measurement units **48** on each of his legs (e.g., on the side or front of his legs). The subject **42** is also provided with two (2) inertial measurement units **48** on each of his arms (e.g., on the side of his arms). In addition, the subject **42** of FIG. **4** is provided with an inertial measurement unit **48** above his waist, and another inertial measurement unit **48** around his or her chest (e.g., near his sternum). In the illustrated embodiment, each of the inertial measurement units **48** is operatively coupled to the data acquisition/data processing device **28** by wireless means, such as Bluetooth, or another suitable type of personal area network wireless means.

In the illustrated embodiment of FIG. **4**, each of the inertial measurement units **48** is coupled to the respective body portion of the subject **42** by a band **50**. As shown in FIG. **4**, each of the inertial measurement units **48** comprises an IMU housing attached to an elastic band **50**. The band **50** is resilient so that it is capable of being stretched while being placed on the subject **42** (e.g., to accommodate the hand or the foot of the subject **42** before it is fitted in place on the arm or the leg of the subject **42**). The band **50** can be formed from any suitable stretchable fabric, such as neoprene, spandex, and elastane. Alternatively, the band **50** could be formed from a generally non-stretchable fabric, and be provided with latching means or clasp means for allowing the band **50** to be split into two portions (e.g., the band **50** could be provided with a snap-type latching device).

In other embodiments, it is possible to attach the inertial measurement units **48** to the body portions of the subject **42** using other suitable attachment means. For example, the inertial measurement units **48** may be attached to a surface (e.g., the skin or clothing item) of the subject **42** using adhesive backing means. The adhesive backing means may comprise a removable backing member that is removed just prior to the inertial measurement unit **48** being attached to a subject **42** or object. Also, in some embodiments, the adhesive backing means may comprise a form of double-sided bonding tape that is capable of securely attaching the inertial measurement unit **48** to the subject **42** or another object.

In one or more embodiments, each inertial measurement unit **48** may comprise a triaxial (three-axis) accelerometer sensing linear acceleration a', a triaxial (three-axis) rate gyroscope sensing angular velocity $\vec{\omega}'$, a triaxial (three-axis) magnetometer sensing the magnetic north vector $\vec{n}'$, and a central control unit or microprocessor operatively coupled to each of accelerometer, gyroscope, and the magnetometer. In addition, each inertial measurement unit **48** may comprise a wireless data interface for electrically coupling the inertial measurement unit **48** to the data acquisition/data processing device **28**.

Next, an illustrative manner in which the data acquisition/data processing device **28** of the gait perturbation system **100** performs the inertial measurement unit (IMU) calculations will be explained in detail. In particular, this calculation procedure will describe the manner in which the orientation and position of one or more body portions (e.g., torso or limbs) of the subject **42** could be determined using the signals from the plurality of inertial measurement units (IMUs) **48** of the motion detection system of FIG. **4**. As explained above, in one or more embodiments, each inertial measurement unit **48** includes the following three triaxial sensor devices: (i) a three-axis accelerometer sensing linear acceleration $\vec{a}'$, (ii) a three-axis rate gyroscope sensing angular velocity $\vec{\omega}'$, and (iii) a three-axis magnetometer sensing the magnetic north vector $\vec{n}'$. Each inertial measurement unit **48** senses in the local (primed) frame of reference attached to the IMU itself. Because each of the sensor devices in each IMU is triaxial, the vectors $\vec{a}'$, $\vec{\omega}'$, $\vec{n}'$ are each 3-component vectors. A prime symbol is used in conjunction with each of these vectors to symbolize that the measurements are taken in accordance with the local reference frame. The unprimed vectors that will be described hereinafter are in the global reference frame.

The objective of these calculations is to find the orientation $\vec{\theta}(t)$ and position $\vec{R}(t)$ in the global, unprimed, inertial frame of reference. Initially, the calculation procedure begins with a known initial orientation $\vec{\theta}_0$ and position $\vec{R}_0$ in the global frame of reference.

For the purposes of the calculation procedure, a right-handed coordinate system is assumed for both global and local frames of reference. The global frame of reference is attached to the Earth. The acceleration due to gravity is assumed to be a constant vector $\vec{g}$. Also, for the purposes of the calculations presented herein, it is presumed the sensor devices of the inertial measurement units (IMUs) provide calibrated data. In addition, all of the signals from the IMUs are treated as continuous functions of time. Although, it is to be understood the general form of the equations described herein may be readily discretized to account for IMU sensor devices that take discrete time samples from a bandwidth-limited continuous signal.

The orientation $\vec{\theta}(t)$ is obtained by single integration of the angular velocity as follows:

$$\vec{\theta}(t)=\vec{\theta}_0+\int_0^t\vec{\omega}(t)dt \tag{2}$$

$$\vec{\theta}(t)=\vec{\theta}_0+\int_0^t\vec{\Theta}(t)\vec{\omega}(t)dt \tag{3}$$

where $\vec{\Theta}(t)$ is the matrix of the rotation transformation that rotates the instantaneous local frame of reference into the global frame of reference.

The position is obtained by double integration of the linear acceleration in the global reference frame. The triaxial accelerometer of each IMU senses the acceleration $\vec{a}'$ in the local reference frame. The acceleration $\vec{a}'$ has the following contributors: (i) the acceleration due to translational motion, (ii) the acceleration of gravity, and (iii) the centrifugal, Coriolis and Euler acceleration due to rotational motion. All but the first contributor has to be removed as a part of the change of reference frames. The centrifugal and Euler accelerations are zero when the acceleration measurements are taken at the origin of the local reference frame. The first integration gives the linear velocity as follows:

$$\vec{v}(t)=\vec{v}_0+\int_0^t\{\vec{a}(t)-\vec{g}\}dt \tag{4}$$

$$\vec{v}(t)=\vec{v}_0+\int_0^t\{\vec{\Theta}(t)[\vec{a}'(t)+2\vec{\omega}'\times\vec{v}'(t)]-\vec{g}\}dt \tag{5}$$

where $2\vec{\omega}'\times\vec{v}'(t)$ is the Coriolis term, and where the local linear velocity is given by the following equation:

$$\vec{v}(t)=\vec{\Theta}^{-1}(t)\vec{v}(t) \tag{6}$$

The initial velocity $\vec{v}_0$ can be taken to be zero if the motion is being measured for short periods of time in relation to the duration of Earth's rotation. The second integration gives the position as follows:

$$\vec{R}(t)=\vec{R}_0+\int_0^t\vec{v}(t)dt \tag{7}$$

At the initial position, the IMU's local-to-global rotation's matrix has an initial value $\vec{\Theta}(0)\equiv\vec{\Theta}_0$. This value can be derived by knowing the local and global values of both the magnetic north vector and the acceleration of gravity. Those two vectors are usually non-parallel. This is the requirement for the $\vec{\Theta}_0(\vec{g}', \vec{n}', \vec{g}, \vec{n})$ to be unique. The knowledge of either of those vectors in isolation gives a family of non-unique solutions $\vec{\Theta}_0(\vec{g}', \vec{g})$ or $\vec{\Theta}_0(\vec{n}', \vec{n})$ that are unconstrained in one component of rotation. The $\vec{\Theta}_0(\vec{g}', \vec{n}', \vec{g}, \vec{n})$ has many implementations, with the common one being the Kabsch algorithm. As such, using the calculation procedure described above, the data acquisition/data processing device **28** of the gait perturbation system **100** may determine the orientation $\vec{\theta}(t)$ and position $\vec{R}(t)$ of one or more body portions of the subject **42**. For example, the orientation of a limb of the subject **42** (e.g., the right arm of the subject **42** in FIG. **4**) may be determined by computing the orientation $\vec{\theta}(t)$ and position $\vec{R}(t)$ of two points on the limb of the subject **42** (i.e., at the respective locations of two inertial measurement units (IMUs) **48** disposed on the limb of the subject **42**).

As explained above, the inertial measurement units (IMUs) **48** of FIG. **4** sense measured quantities (i.e., acceleration, angular velocity) that are representative of the position of the body portion of the subject **42** and output a plurality of position data signals that are representative of the position of the body portion of the subject **42**. The data acquisition/data processing device **28** is specially programmed to determine the position of the body portion of the subject **42** using the plurality of position data signals that are output by the plurality of inertial measurement units **48** (e.g., the plurality of position data signals from the inertial measurement units **48** may be used to determine the position of the subject **42** relative to the center of the treadmill belts **14**, **16** or to approximate the subject's center-of-gravity along the y-axis).

Now, the manner in which the programmable logic controller **25** and data acquisition/data processing device **28** of the gait perturbation system **100** are specially programmed to perturb the gait of the subject **42** disposed on the instrumented treadmill **10** will be described. As explained above, the data acquisition/data processing device **28** is operatively coupled to the programmable logic controller **25** of the instrumented treadmill **10**. In one illustrative embodiment, the programmable logic controller **25** (i.e., a data processing device) is specially programmed to generate a first base velocity signal for controlling the speed of the treadmill belts **14**, **16** of the instrumented treadmill **10** and a second velocity signal for introducing a perturbation to the treadmill belts **14**, **16**. Also, in the illustrative embodiment, programmable logic controller **25** is specially programmed to combine the first base velocity signal with the second velocity signal to form a composite velocity signal, and to control the speed set points of the treadmill belts **14**, **16** using the composite velocity signal such that the treadmill belts **14**, **16** perturb a gait of the person. As described in detail hereinafter, in order to create perturbations, the frequency and the amplitude of the treadmill belt speed can be varied. In an alternative illustrative embodiment, the data acquisition/data processing device **28**, rather than the programmable logic controller **25**, may be specially programmed to generate the first base velocity signal for controlling the speed of the treadmill belts **14**, **16** of the instrumented treadmill **10**, to generate the second velocity signal for introducing a perturbation to the treadmill belts **14**, **16**, and to combine the first base velocity signal and the second velocity signal to form the composite velocity signal.

An exemplary base velocity signal generated by the programmable logic controller **25** or the data acquisition/data processing device **28** for controlling the speed of the treadmill belts **14**, **16** of the instrumented treadmill **10** is illustrated in the graph **62** of FIG. **7**. As shown in this figure, the y-axis **64** of the graph **62** is the treadmill belt speed in meters per second (m/s), while the x-axis **66** of the graph **62** is the time in milliseconds (ms). In the graph **62** of FIG. **7**, it can be seen that the base velocity curve **68** ramps up to 1.0 meters per second at approximately 2,000 milliseconds and then ramps down back to zero at approximately 18,000 milliseconds. In FIG. **7**, no perturbations have been applied to the treadmill belts **14**, **16**.

In the illustrative embodiment, the second velocity signal for introducing a perturbation to the treadmill belts **14**, **16** comprises a stochastic signal, and the programmable logic controller **25** or the data acquisition/data processing device **28** is specially programmed to add the stochastic signal to the base velocity signal so as to make the treadmill belts **14**, **16** oscillate while the subject **42** is disposed thereon. As will be described hereinafter, the stochastic signal may be of uniform or normal distribution. As such, the stochastic signal is capable of simulating uneven terrain or slips and falls while the subject **42** is walking or running on the instrumented treadmill **10**.

An exemplary combined base velocity and stochastic signal generated by the programmable logic controller **25** or the data acquisition/data processing device **28** for controlling the speed of the treadmill belts **14**, **16** of the instrumented treadmill **10** is illustrated in the graph **70** of FIG. **8**. As shown in this figure, the y-axis **72** of the graph **70** is the treadmill belt speed in meters per second (m/s), while the x-axis **74** of the graph **70** is the time in milliseconds (ms). In the graph **70** of FIG. **8**, it can be seen that the combined base velocity/stochastic signal curve comprises a base velocity curve portion **76** and stochastic signal curve portion **78**. The base velocity curve portion **76** ramps up to 1.0 meters per second at approximately 2,000 milliseconds and then ramps down back to zero at approximately 22,000 milliseconds. In FIG. **8**, the stochastic signal is added to the base velocity signal of 1.0 meters per second. As shown in FIG. **8**, the combined base velocity and stochastic signal generated by the programmable logic controller **25** or the data acquisition/data processing device **28** is never negative, so the belts **14**, **16** of the instrumented treadmill do not undergo a change in their rotational directions over time (i.e., because the velocity is always a positive value, the direction of the belts **14**, **16** is not reversed in the exemplary signal of FIG. **8**). As shown in FIG. **8**, the amplitude of the stochastic signal curve portion **78** is randomly changing over time (i.e., the amplitude consistently changes over time in a random manner). Similarly, the frequency of the stochastic signal curve portion **78** is randomly changing over time (i.e., the frequency consistently changes over time in a random manner). Thus, advantageously, the programmable logic controller **25** or the data acquisition/data processing device **28** generates a stochastic signal with both a randomly varying amplitude and frequency that results in a random perturbation being delivered to the subject **42** on the instrumented treadmill **10**. The manner of delivery of the perturbation to the subject **42** on the treadmill **10** is not just random, but rather the stochastic signal itself controlling the perturbation has both random amplitude and frequency content. Advantageously, the belt speed of the instrumented treadmill **10** does not have a constant slope that can be learned by the subject **42** over time. The stochastic signal generated by the programmable logic controller **25** or the data acquisition/data processing device **28** significantly changes the functionality of the instrumented treadmill **10** by enabling the instrumented treadmill **10** to simulate unexpected, real-life scenarios that could be encountered by the subject **42**, such as slip and fall events. As such, controlling the treadmill **10** using the stochastic signal enables the instrumented treadmill **10** to model real-life conditions encountered by the subject **42** so that the testing and/or training of the subject **42** using the treadmill **10** may be greatly enhanced.

In the illustrative embodiment, the generation of the combined base velocity and stochastic signal by the programmable logic controller **25** or the data acquisition/data processing device **28** comprises a plurality of different steps. Initially, by utilizing the input devices **32**, **36** of the data acquisition/data processing device **28** (e.g., the keyboard **32** and/or touchpad **36**), a user enters the following input values: (i) the stochastic signal base amplitude, (ii) a frequency of the stochastic signal (i.e., the cut-off frequency of the stochastic signal), and (iii) a signal type of the stochastic signal (i.e., uniform or random). Then, the programmable logic controller **25** or the data acquisition/data processing device **28** generates the random or uniform stochastic signal based upon the amplitude and frequency values entered by the user. The amplitude value entered by the user determines the upper and lower bounds of the stochastic signal generated by the programmable logic controller **25** or the data acquisition/data processing device **28**, while the cut-off frequency value entered by the user determines the upper frequency limit of the stochastic signal generated by the programmable logic controller **25** or the data acquisition/data processing device **28**. Finally, the programmable logic controller **25** updates belt speed set point(s) of the treadmill belts **14**, **16** of the instrumented treadmill **10**. Each of these steps will be described in further detail hereinafter. Referring to FIG. **6**, when the programmable logic controller **25** generates the stochastic signal, the base amplitude, the cut-off frequency, and the signal type of the stochastic signal are transmitted from the data acquisition/data processing device **28** to the programmable logic controller **25** so that the stochastic signal is able to be generated by the programmable logic controller **25**.

In the illustrative embodiment, the user may be permitted to enter a stochastic amplitude value in the range between zero and approximately 2.0 meters, inclusive (or between zero and 2.0 meters, inclusive). If the user enters different amplitude values for each of the treadmill belts **14**, **16**, the difference in the two amplitude values may not exceed 1.0 meter in the illustrative embodiment. Similarly, in the illustrative embodiment, the user may be permitted to enter a cut-off frequency value in the range between zero and approximately 10 Hertz, inclusive (or between zero and 10 Hertz, inclusive). If the user enters different cut-off frequency values for each of the treadmill belts **14**, **16**, the difference in the cut-off frequency values may not exceed 5 Hertz in the illustrative embodiment. Also, in the illustrative embodiment, the amplitude has to be less than the base velocity (e.g., if the base velocity is 2.0 meters per second, then the amplitude needs to be less than 2.0 meters). In general, a low amplitude would simulate vibrations, while a high amplitude would imitate a slip condition.

In addition to entering the amplitude, cut-off frequency, and signal type of the stochastic signal, the user is also able to selectively regulate the beginning and end of the stochastic signal by pressing a graphical start button on the operator display **34** to initiate the stochastic signal, and then by subsequently pressing a graphical stop button on the operator display **34** to end the stochastic signal (i.e., when the display is a touchscreen).

In the illustrative embodiment, the belt speed of each belt **14**, **16** of the instrumented dual belt treadmill **10** is capable of being updated independently. In the initial step of the process, as explained above, the user is allowed to input the amplitude of the stochastic signal, the frequency of the stochastic signal, and the stochastic signal type (i.e., either uniform or normal). The base amplitude that is input for the signal determines the range of the stochastic signal that is generated by the programmable logic controller **25** or the data acquisition/data processing device **28**. For example, a first exemplary uniform stochastic signal generated by the programmable logic controller **25** or the data acquisition/data processing device **28** is illustrated in the graph **80** of FIG. **9**. As shown in this figure, the y-axis **82** of the graph **80** is speed in meters per second (m/s), while the x-axis **84** of the graph **80** is the time in milliseconds (ms). The uniform stochastic signal curve **86** in FIG. **9** has a base amplitude of 0.9 meters and a cut-off frequency of 5 Hertz. In the graph **80** of FIG. **9**, it can be seen that the uniform stochastic signal curve **86** oscillates between a minimum lower limit of approximately −0.40 meters per second and a maximum upper limit of approximately 0.40 meters per second over a time duration of approximately 10,000 milliseconds. As another example, a second exemplary uniform stochastic signal generated by the programmable logic controller **25** or the data acquisition/data processing device **28** is illustrated in the graph **88** of FIG. **10**. As shown in this figure, the y-axis **90** of the graph **88** is speed in meters per second (m/s), while the x-axis **92** of the graph **88** is the time in milliseconds (ms). The uniform stochastic signal curve **94** in FIG. **10** has a base amplitude of 0.5 meters and a cut-off frequency of 5 Hertz. In the graph **88** of FIG. **10**, it can be seen that the uniform stochastic signal curve **94** oscillates between a minimum lower limit of approximately −0.25 meters per second and a maximum upper limit of approximately 0.225 meters per second over a time duration of approximately 10,000 milliseconds.

As yet another example of a perturbation input signal, an exemplary normal stochastic signal generated by the programmable logic controller **25** or the data acquisition/data processing device **28** is illustrated in the graph **96** of FIG. **11**. As shown in this figure, the y-axis **98** of the graph **96** is speed in meters per second (m/s), while the x-axis **101** of the graph **96** is the time in milliseconds (ms). The normal stochastic signal curve **102** in FIG. **11** has a base amplitude of 0.9 meters and a cut-off frequency of 5 Hertz. In the graph **96** of FIG. **11**, it can be seen that the normal stochastic signal curve **102** oscillates between a minimum lower limit of approximately −0.25 meters per second and a maximum upper limit of approximately 0.25 meters per second over a time duration of approximately 10,000 milliseconds. As still another example, a third exemplary uniform stochastic signal generated by the programmable logic controller **25** or the data acquisition/data processing device **28** is illustrated in the graph **104** of FIG. **12**. As shown in this figure, the y-axis **106** of the graph **104** is speed in meters per second (m/s), while the x-axis **108** of the graph **104** is the time in milliseconds (ms). The uniform stochastic signal curve **110** in FIG. **12** has a base amplitude of 0.9 meters and a cut-off frequency of 10 Hertz. In the graph **104** of FIG. **12**, it can be seen that the uniform stochastic signal curve **110** oscillates between a minimum lower limit of approximately −0.30 meters per second and a maximum upper limit of approximately 0.36 meters per second over a time duration of approximately 6,000 milliseconds.

In the second step of the process, where a random uniform or normal random signal is generated by the programmable logic controller **25** or the data acquisition/data processing device **28** at the selected cut-off frequency, a random number function or subroutine may be used to generate the uniform signal random numbers (e.g., the DRAND function block in a TwinCAT software package). In the illustrative embodiment, the random number function utilized by the programmable logic controller **25** or the data acquisition/data processing device **28** requires an initial value input for the specification of the random number series. The output returns a pseudo-random number in the range −1.0 to 1.0 with double accuracy. That is, the random number function generates the same sequence of random numbers each time that the same seed is utilized. As such, in an exemplary embodiment, the seed value that is used for the random number function is acquired for each trial from the low DW of the system time, which gives a sufficiently random seed for each trial. That way, the programmable logic controller **25** or the data acquisition/data processing device **28** does not generate the same random number sequence or produce any other perturbation trends from trial to trial. In one or more embodiments, the operating system time stamp is a 64-bit integer value, with a precision of 100 nanoseconds (ns), which is updated with every call of the programmable logic controller (PLC) **25**. In one or more embodiments, the low DW (timeLoDW) is the low-value 4 bytes of the time stamp and it changes very rapidly at rate of 0.01 milliseconds (ms). The random signal has a varying frequency. The randomness of the stochastic signal is highly advantageous because the subjects being tested on the instrumented treadmill **10** are not able to as easily learn how to overcome a slip-and-fall perturbation during a testing or training routine. If the perturbation employed was always the same, then eventually subjects would learn how to adapt to the perturbation, and the training would become less effective.

An exemplary uniform random numbers curve generated by the programmable logic controller **25** or data acquisition/data processing device **28** using a random number function or subroutine (e.g., DRAND function block) is illustrated in the graph **112** of FIG. **13**. As shown in this figure, the y-axis **114** of the graph **112** is the random number value (dimensionless), while the x-axis **116** of the graph **112** is the time in milliseconds (ms). In the graph **112** of FIG. **13**, it can be seen that the uniform random numbers curve **118** comprises a plurality of random number values between a lower limit value of approximately −0.95 and an upper limit value of approximately 0.90.

When the user selects a uniform-type stochastic signal, a uniform random numbers curve, such as that depicted in FIG. **13**, is used for controlling the speed set points of the belts **14**, **16** of the instrumented dual belt treadmill **10**. However, if the user alternatively selects a normal-type stochastic signal, two (2) uniform signals U**1** and U**2** generated using the random number function are converted into normal signal N using the following Box-Muller transform equation:

$$N=\sqrt{-2\ln U1}\cos(2\pi U2) \quad (8)$$

An exemplary normal random numbers curve generated by the programmable logic controller **25** or the data acquisition/data processing device **28** using equation (8) to perform a Box-Muller transformation is illustrated in the graph **120** of FIG. **14**. As shown in this figure, the y-axis **122** of the graph **120** is the random number value (dimensionless), while the x-axis **124** of the graph **120** is the time in milliseconds (ms). In the graph **120** of FIG. **14**, it can be seen that the normal random numbers curve **126** comprises a plurality of random number values between a lower limit value of approximately −1.2 and an upper limit value of approximately 2.8. The random variables illustrated in FIG. **14** are generated in the interval [3,−3].

In the illustrative embodiment, the uniform or normal signal is then passed through a fourth order low pass Butterworth filter to limit the frequency component of the signal at a user specified value (i.e., at the frequency entered by the user). For example, a first exemplary filtered signal generated by the programmable logic controller **25** or the data acquisition/data processing device **28** is illustrated in the graph **128** of FIG. **15**. As shown in this figure, the y-axis

130 of the graph 128 is the amplitude value of the signal (dimensionless), while the x-axis 132 of the graph 128 is the frequency of the signal in Hertz (Hz). In the graph 128 of FIG. 15, the unfiltered normal signal curve 134 is indicated using a dashed line, while the filtered normal signal curve 136 is indicated using a solid line. In FIG. 15, a cut-off frequency of 5 Hertz is used in order to generally filter out the frequency content of the normal signal curve 134 which has a frequency of greater than 5 Hertz. As such, the frequency content of the normal signal curve used for controlling the perturbation of the instrumented treadmill 10 is generally limited to the user-specified frequency of 5 Hertz in FIG. 15. As another example, a second exemplary filtered signal generated by the programmable logic controller 25 or the data acquisition/data processing device 28 is illustrated in the graph 138 of FIG. 16. As shown in this figure, the y-axis 140 of the graph 138 is the amplitude value of the signal (dimensionless), while the x-axis 142 of the graph 138 is the frequency of the signal in Hertz (Hz). In the graph 138 of FIG. 16, the unfiltered normal signal curve 144 is indicated using a dashed line, while the filtered normal signal curve 146 is indicated using a solid line. In FIG. 16, a cut-off frequency of 10 Hertz is used in order to generally filter out the frequency content of the normal signal curve 144 which has a frequency of greater than 10 Hertz. As such, the frequency content of the normal signal curve used for controlling the perturbation of the instrumented treadmill 10 is generally limited to the user-specified frequency of 10 Hertz in FIG. 16.

Turning to FIG. 17, it can be seen that a graph 148 comparing the filtered data with cut-off frequencies of 5 Hertz and 10 Hertz is illustrated therein. Similar to FIGS. 15 and 16 described above, the y-axis 150 of the graph 148 depicted in FIG. 17 is the amplitude value of the signal (dimensionless), while the x-axis 152 of the graph 148 is the frequency of the signal in Hertz (Hz). In the graph 148 of FIG. 17, the filtered data curve 156 with a cut-off frequency of 5 Hertz is indicated using a solid line, while the filtered data curve 154 with a cut-off frequency of 10 Hertz is indicated using a dashed line.

In the illustrative embodiment, prior to the third step of the process, where the programmable logic controller 25 or the data acquisition/data processing device 28 updates belt speed set point(s) of the treadmill belts 14, 16 of the instrumented treadmill 10, the filtered signal is multiplied by the user-specified amplitude value so as to generate the stochastic signal for updating the belt speed set point(s). When the uniform-type stochastic signal is selected by the user, the uniform stochastic signal for updating the belt speed set point(s) is determined by the programmable logic controller 25 or the data acquisition/data processing device 28 in accordance with the following equation:

$$\text{Uniform stochastic signal}=\text{filtered uniform signal}*\text{Amplitude} \tag{9}$$

Thus, in accordance with equation (9) above, the uniform stochastic signal is a function of the filtered, randomly-generated uniform signal and the user-specified amplitude value. More specifically, the programmable logic controller 25 or the data acquisition/data processing device 28 determines the uniform stochastic signal by computing the multiplicative product between the filtered uniform signal and the user-specified amplitude value. Alternatively, when the normal-type stochastic signal is selected by the user, the normal stochastic signal for updating the belt speed set point(s) is determined by the programmable logic controller 25 or the data acquisition/data processing device 28 in accordance with the following equation:

$$\text{Normal stochastic signal}=\text{filtered normal signal}*\text{Amplitude}/3 \tag{10}$$

Thus, in accordance with equation (10) above, the normal stochastic signal is a function of the filtered, normalized randomly-generated uniform signal and the user-specified amplitude value. More specifically, the programmable logic controller 25 or the data acquisition/data processing device 28 determines the normal stochastic signal by computing the multiplicative product between the filtered normal signal and one-third of the user-specified amplitude value.

In one or more embodiments, the aforedescribed belt speed calculations are specially programmed on an embedded computer (e.g., the programmable logic controller 25 or the data acquisition/data processing device 28) that provides a deterministic program cycle time of 1 milliseconds (ms). In other words, the belt speed update rate of 1 kilohertz (kHz) is guaranteed by either the hardware architecture of the embedded computer or a real-time operating system (e.g., firmware) that runs on it. In these one or more embodiments, the updated belt speed set points are sent to a servo controller (i.e., actuator control drive 27), which controls the belt motor speed with a closed-loop rate of 4 kilohertz (kHz). In these one or more embodiments, the firmware of the instrumented treadmill 10 controls the treadmill belt perturbations.

In the illustrative embodiment, the programmable logic controller 25 or the data acquisition/data processing device 28 may be specially programmed so as to enable the belts 14, 16 of the instrumented treadmill 10 to be controlled in two different modes: (i) a dual stochastic mode, and (ii) independent left/right stochastic mode. In the dual stochastic mode, the programmable logic controller 25 or the data acquisition/data processing device 28 controls the speed set point of each of the treadmill belts 14, 16 using the same combined base velocity and stochastic signal so that the belts 14, 16 rotate together in unison. In the independent left/right stochastic mode, the programmable logic controller 25 or the data acquisition/data processing device 28 controls the speed set point of each of the treadmill belts 14, 16 using different combined base velocity and stochastic signals so that the belts 14, 16 do not rotate together (i.e., the belt speed set point of the left belt 14 is controlled independently from the belt speed set point of the right belt 16).

In a further embodiment, the programmable logic controller 25 or the data acquisition/data processing device 28 may be specially programmed to additionally control the belts 14, 16 of the instrumented treadmill 10 in a pulsed mode of operation. In the pulsed operation mode, the belts 14, 16 of the instrumented treadmill 10 are displaced from an initial stationary position (i.e., the belts 14, 16 undergo pure translation from a standstill position). In the pulsed mode of operation, the maximum pulse distance may be approximately 1.25 meters (or 1.25 m), the maximum pulse velocity may be approximately 6.5 meters per second (or 6.5 m/s), the maximum pulse acceleration may be approximately 10.0 meters per second squared (or 10 m/s^2), the maximum pulse deceleration may be approximately 10.0 meters per second squared (or 10 m/s^2), the maximum difference in the pulse distance between the treadmill belts 14, 16 may be approximately 1.0 meter (or 1 m), the maximum difference in the pulse velocity between the treadmill belts 14, 16 may be approximately 5.5 meters per second (or 5.5 m/s), the maximum difference in the pulse acceleration between the treadmill belts 14, 16 may be approximately 9.0 meters per second squared (or 9.0 m/s^2), and the maximum difference in the pulse deceleration between the treadmill belts **14**, **16** may be approximately 9.0 meters per second squared (or 9.0 m/s^2).

An illustrative embodiment of a balance perturbation system is seen generally at **200** in FIG. **18**. In the second illustrative embodiment, the balance perturbation system **200** generally comprises a force measurement assembly **202** that is operatively coupled to a data acquisition/data processing device **204** (i.e., a data acquisition and processing device or computing device that is capable of collecting, storing, and processing data), which in turn, is operatively coupled to a subject visual display device **207** and an operator visual display device **230**. As illustrated in FIG. **18**, the force measurement assembly **202** is configured to receive a subject **208** thereon, and is capable of measuring the forces and/or moments applied to its substantially planar measurement surfaces **214**, **216** by the subject **208**.

As shown in FIG. **18**, the data acquisition/data processing device **204** includes a plurality of user input devices **232**, **234** connected thereto. Preferably, the user input devices **232**, **234** comprise a keyboard **232** and a mouse **234**. In addition, the operator visual display device **230** may also serve as a user input device if it is provided with touch screen capabilities. While a desktop-type computing system is depicted in FIG. **18**, one of ordinary of skill in the art will appreciate that another type of data acquisition/data processing device **204** can be substituted for the desktop computing system such as, but not limited to, a laptop or a palmtop computing device (i.e., a PDA).

Referring again to FIG. **18**, it can be seen that the force measurement assembly **202** of the second illustrated embodiment is in the form of a displaceable, dual force plate assembly. The displaceable, dual force plate assembly includes a first plate component **210**, a second plate component **212**, at least one force measurement device (e.g., a force transducer) associated with the first plate component **210**, and at least one force measurement device (e.g., a force transducer) associated with the second plate component **212**. In the illustrated embodiment, a subject **208** stands in an upright position on the force measurement assembly **202** and each foot of the subject **208** is placed on the top surfaces **214**, **216** of a respective plate component **210**, **212** (i.e., one foot on the top surface **214** of the first plate component **210** and the other foot on the top surface **216** of the second plate component **212**). The at least one force transducer associated with the first plate component **210** is configured to sense one or more measured quantities and output one or more first signals that are representative of forces and/or moments being applied to its measurement surface **214** by the left foot/leg **208***a* of the subject **208**, whereas the at least one force transducer associated with the second plate component **212** is configured to sense one or more measured quantities and output one or more second signals that are representative of forces and/or moments being applied to its measurement surface **216** by the right foot/leg **208***b* of subject **208**. In one or more embodiments, when the subject is displaced on the force measurement assembly **202**, the subject **208** generally does not move relative to the displaceable force measurement assembly **202** (i.e., the subject **208** and the force measurement assembly **202** generally move together in synchrony). Also, in one or more embodiments, the top surfaces **214**, **216** of the respective plate components **210**, **212** are not rotated underneath the feet of the subject **208**, but rather remain stationary relative to the feet of the subject **208** (i.e., the top surfaces **214**, **216** are displaced in generally the same manner as the feet of the subject).

In one non-limiting, exemplary embodiment, the force plate assembly **202** has a load capacity of up to approximately 500 lbs. (up to approximately 2,224 N) or up to 500 lbs. (up to 2,224 N). Advantageously, this high load capacity enables the force plate assembly **202** to be used with almost any subject requiring testing on the force plate assembly **202**. Also, in one non-limiting, exemplary embodiment, the force plate assembly **202** has a footprint of approximately eighteen (18) inches by twenty (20) inches. However, one of ordinary skill in the art will realize that other suitable dimensions for the force plate assembly **202** may also be used.

Now, with reference to FIG. **19**, it can be seen that the displaceable force measurement assembly **202** is movably coupled to a base assembly **206**. The base assembly **206** generally comprises a substantially planar center portion **206***b* with two spaced-apart side enclosures **206***a*, **206***c* that are disposed on opposed sides of the center portion **206***b*. As shown in FIG. **19**, the displaceable force measurement assembly **202** is recessed-mounted into the top surface of the center portion **206***b* of the base assembly **206** (i.e., it is recess-mounted into the top surface of the translatable sled assembly **256** which is part of the center portion **206***b* of the base assembly **206**) so that its upper surface lies substantially flush with the adjacent stationary top surfaces **222***a*, **222***b* of the center portion **206***b* of the base assembly **206**. The upper surface of the displaceable force measurement assembly **202** also lies substantially flush with the top surface of the translatable sled assembly **256**. Moreover, in the illustrated embodiment, it can be seen that the base assembly **206** further includes a pair of mounting brackets **224** disposed on the outward-facing side surfaces of each side enclosure **206***a*, **206***c*. Each mounting bracket **224** accommodates a respective support rail **228**. The support rails **228** can be used for various purposes related to the balance perturbation system **200**. For example, the support rails **228** can be used for supporting a safety harness system, which is worn by the subject during testing so as to prevent injury.

Referring again to FIG. **19**, each side enclosure **206***a*, **206***c* houses a plurality of electronic components that generate a significant amount of waste heat that requires venting. Because the bottom of each side enclosure **206***a*, **206***c* is substantially open, the waste heat is vented through the bottom thereof. In FIG. **19**, it can be seen that the side enclosure **206***a* comprises an emergency stop switch **238** (E-stop) provided in the rear, diagonal panel thereof. In one embodiment, the emergency stop switch **238** is in the form of a red pushbutton that can be easily pressed by a user of the balance perturbation system **200** in order to quasi-instantaneously stop the displacement of the force measurement assembly **202**. As such, the emergency stop switch **238** is a safety mechanism that protects a subject disposed on the displaceable force measurement assembly **202** from potential injury.

Next, turning to FIG. **20**, the drive components of the base assembly **206** will be described in detail. Initially, the actuator system for producing the translation of the force measurement assembly **202** will be explained. In FIG. **20**, the front top cover of the center portion **206***b* of the base assembly **206** has been removed to reveal the translation drive components. As shown in this figure, the force measurement assembly **202** is rotatably mounted to a translatable sled assembly **256**. The translatable sled assembly **256** is displaced forward and backward (i.e., in directions generally parallel to the sagittal plane SP of the subject (see e.g., FIG. **18**) disposed on the force measurement assembly **202**) by means of a first actuator assembly **258**. That is, the first actuator assembly **258** moves the translatable sled assembly **256** backwards and forwards, without any substantial rotation or angular displacement (i.e., the first actuator assembly **258** produces generally pure translational movement). In the illustrated embodiment, the first actuator assembly **258** is in the form of ball screw actuator, and includes an electric motor that drives a rotatable screw shaft which, in turn, is threadingly coupled to a nut fixedly secured to the translatable sled assembly **256**. As such, when the screw shaft of the first actuator assembly **258** is rotated by the electric motor, the translatable sled assembly is displaced forward and backward along a substantially linear path. The electric motor of the first actuator assembly **258** is operatively coupled to a gear box (e.g., a 4:1 gear box) which, in turn, drives the rotatable screw shaft. Advantageously, because the nut of the ball screw actuator runs on ball bearings, friction is minimized and the actuator assembly **258** is highly efficient. However, an undesirable consequence of the highly efficient ball screw actuator design is its back-driveability. This poses a potential safety hazard to a subject disposed on the displaceable force measurement assembly **202** because the force plate could inadvertently move when a subject's weight is applied thereto. In order to prevent the force measurement assembly **202** from inadvertently being translated, the first actuator assembly **258** is additionally provided with a brake assembly disposed adjacent to the electric motor thereof. The brake assembly of the first actuator assembly **258** prevents any unintentional translation of the force measurement assembly **202**.

In FIG. **21**, a top view of the base assembly **206** is illustrated, while in FIG. **22**, a longitudinal cross-sectional view of the base assembly **206** is illustrated. As shown in FIGS. **21** and **22**, the force measurement assembly **202** is mounted on a rotatable carriage assembly **257** (i.e., a swivel frame **257**). The rotatable carriage assembly **257** is mounted to, and rotates relative to, the translatable sled assembly **256** (i.e., the translatable frame **256**). The rotatable carriage assembly **257** is rotated by a second actuator assembly **260** (see FIG. **20**) about a rotational shaft **263** (see FIG. **22**—the rotatable carriage assembly **257** is provided with diagonal hatching thereon). As indicated by the curved arrows **259** in FIG. **22**, the rotatable carriage assembly **257** is capable of either clockwise or counter-clockwise rotation about the transverse rotational axis TA in FIG. **20** (i.e., generally single degree-of-freedom rotation about the transverse axis TA). In contrast, as indicated by the straight arrows **261** in FIGS. **21** and **22**, the translatable sled assembly **256** is capable of forward and backward translational movement by virtue of being linearly displaced by first actuator assembly **258**. In FIGS. **21** and **22**, a rearwardly displaced position **256*a*** of the translatable sled assembly **256** is indicated using center lines, while a forwardly displaced position **256*b*** of the translatable sled assembly **256** is indicated using dashed lines with small dashes.

Again, referring to FIG. **20**, the actuator system for producing the rotation of the force measurement assembly **202** will now be described. In FIG. **20**, the top cover of the side enclosure **206*c*** of the base assembly **206** has been removed to reveal the rotational drive components. The force measurement assembly **202** is rotated within the translatable sled assembly **256** by the second actuator assembly **260**. Like the first actuator assembly **258**, the second actuator assembly **260** is also in the form of ball screw actuator, and includes an electric motor with a gear box (e.g., a 4:1 gear box) that drives a rotatable screw shaft which, in turn, is threadingly coupled to a nut that runs on ball bearings. Although, unlike the first actuator assembly **258**, the second actuator assembly **260** further includes a swing arm which is operatively coupled to the nut of the ball screw actuator. When the nut undergoes displacement along the screw shaft, the swing arm, which is attached to the rotatable carriage assembly **257** with the force measurement assembly **202**, is rotated. As such, when the swing arm is rotated, the rotatable carriage assembly **257** with the force measurement assembly **202** is also rotated about a transverse rotational axis TA (see FIG. **20**). That is, the force measurement assembly **202** undergoes generally single degree-of-freedom rotation about the transverse rotational axis TA. In one embodiment, the imaginary transverse rotational axis TA approximately passes through the center of the ankle joints of the subject **208** when he or she is disposed on the force measurement assembly **202**. Because the second actuator assembly **260** is also in the form of a highly efficient ball screw actuator, it includes a brake assembly disposed adjacent to the electric motor to prevent it from being back-driven, similar to that of the first actuator assembly **258**. The brake assembly of the second actuator assembly **260** prevents the force measurement assembly **202** from being inadvertently rotated so as to protect a subject disposed thereon from its inadvertent movement. When the translatable sled assembly **256** is translated by the first actuator assembly **258**, the second actuator assembly **260** is translated with the sled assembly **256** and the force plate. In particular, when the translatable sled assembly **256** is translated backwards and forwards by the first actuator assembly **258**, the second actuator assembly **260** is displaced along a rail or rod of the base assembly **206**.

In a preferred embodiment of the invention, both the first actuator assembly **258** and the second actuator assembly **260** are provided with two (2) electrical cables operatively coupled thereto. The first cable connected to each actuator assembly **258**, **260** is a power cable for the electric motor and brake of each actuator, while the second cable transmits positional information from the respective actuator encoder that is utilized in the feedback control of each actuator assembly **258**, **260**.

Referring back to FIG. **18**, it can be seen that the base assembly **206** is operatively coupled to the data acquisition/data processing device **204** by virtue of an electrical cable **218**. The electrical cable **218** is used for transmitting data between the programmable logic controller (PLC) of the base assembly **206** and the data acquisition/data processing device **204** (i.e., the operator computing device **204**). Various types of data transmission cables can be used for cable **218**. For example, the cable **218** can be a Universal Serial Bus (USB) cable or an Ethernet cable. Preferably, the electrical cable **218** contains a plurality of electrical wires bundled together that are utilized for transmitting data. However, it is to be understood that the base assembly **206** can be operatively coupled to the data acquisition/data processing device **204** using other signal transmission means, such as a wireless data transmission system.

In the illustrated embodiment, the at least one force transducer associated with the first and second plate components **210**, **212** comprises four (4) pylon-type force transducers **254** (or pylon-type load cells) that are disposed underneath, and near each of the four corners (4) of the first plate component **210** and the second plate component **212** (see FIG. **23**). Each of the eight (8) illustrated pylon-type force transducers has a plurality of strain gages adhered to the outer periphery of a cylindrically-shaped force transducer sensing element for detecting the mechanical strain of the force transducer sensing element imparted thereon by the force(s) applied to the surfaces of the force measurement assembly **202**. As shown in FIG. **23**, a respective base plate **262** can be provided underneath the transducers **254** of each plate component **210**, **212** for facilitating the mounting of the force plate assembly to the rotatable carriage assembly **257** of the translatable sled assembly **256** of the base assembly **206**. Alternatively, a plurality of structural frame members (e.g., formed from steel) could be used in lieu of the base plates **262** for attaching the dual force plate assembly to the rotatable carriage assembly **257** of the translatable sled assembly **256** of the base assembly **206**. Also, in one or more other embodiments, the force measurement assembly **202** may comprise a single force plate in lieu of the dual force plate of FIGS. **23** and **24**.

In an alternative embodiment, rather than using four (4) pylon-type force transducers **254** on each plate component **210**, **212**, force transducers in the form of transducer beams could be provided under each plate component **210**, **212**. In this alternative embodiment, the first plate component **210** could comprise two transducer beams that are disposed underneath, and on generally opposite sides of the first plate component **210**. Similarly, in this embodiment, the second plate component **212** could comprise two transducer beams that are disposed underneath, and on generally opposite sides of the second plate component **212**. Similar to the pylon-type force transducers **254**, the force transducer beams could have a plurality of strain gages attached to one or more surfaces thereof for sensing the mechanical strain imparted on the beam by the force(s) applied to the surfaces of the force measurement assembly **202**.

Rather, than using four (4) force transducer pylons under each plate, or two spaced apart force transducer beams under each plate, it is to be understood that the force measurement assembly **202** can also utilize the force transducer technology described in U.S. Pat. No. 8,544,347, the entire disclosure of which is incorporated herein by reference.

Referring to FIGS. **19** and **20**, the base assembly **206** is preferably provided with a plurality of support feet **226** disposed thereunder. Preferably, each of the four (4) corners of the base assembly **206** is provided with a support foot **226**. In one embodiment, each support foot **226** is attached to a bottom surface of base assembly **206**. In one preferred embodiment, at least one of the support feet **226** is adjustable so as to facilitate the leveling of the base assembly **206** on an uneven floor surface (e.g., see FIG. **20**, the support foot can be provided with a threaded shaft **229** that permits the height thereof to be adjusted). For example, referring to FIG. **19**, the right corner of the base assembly **206** may be provided with a removable cover plate **227** for gaining access to an adjustable support foot **226** with threaded shaft **229**.

In one exemplary embodiment, with reference to FIG. **19**, the base assembly **206** has a length L_B of approximately five feet (5'-0"), a width W_B of approximately five feet (5'-0"), and a step height H_B of approximately four (4) inches. In other words, the base assembly has an approximately 5'-0" by 5'-0" footprint with step height of approximately four (4) inches. In other exemplary embodiments, the base assembly **206** has a width W_B of slightly less than five feet (5'-0"), for example, a width W_B lying in the range between approximately fifty-two (52) inches and approximately fifty-nine (59) inches (or between fifty-two (52) inches and fifty-nine (59) inches). Also, in other exemplary embodiments, the base assembly **206** has a step height lying in the range between approximately four (4) inches and approximately four and one-half (4½) inches (or between four (4) inches and four and one-half (4½) inches). Advantageously, the design of the base assembly **206** is such that its step height is minimized. For example, the placement of the second actuator assembly **260** above the top surface of the base assembly **206** facilitates a reduction in the step height of the base assembly **206**. It is highly desirable for the base assembly **206** to have as low a profile as possible. A reduced step height especially makes it easier for subjects having balance disorders to step on and off the base assembly **206**. This reduced step height is particularly advantageous for elderly subjects or patients being tested on the balance perturbation system **200** because it is typically more difficult for elderly subjects to step up and down from elevated surfaces.

Now, with reference to FIGS. **18-20**, the subject visual display device **207** of the balance perturbation system **200** will be described in more detail. In one exemplary embodiment, the subject visual display device **207** may comprise a projector, a generally spherical mirror (i.e., a convexly curved mirror that has the shape of a piece cut out of a spherical surface), and a generally hemispherical concave projection screen **268** with a variable radius (i.e., the radius of the hemispherical projection screen **268** becomes increasingly larger from its center to its periphery). As shown in FIG. **18**, the hemispherical projection screen **268** may be provided with a peripheral flange **269** therearound. In one exemplary embodiment, the lens of the projector projects an image onto the generally spherical mirror which, in turn, projects the image onto the generally hemispherical projection screen **268**. Advantageously, the generally hemispherical projection screen **268** is a continuous curved surface that does not contain any lines or points resulting from the intersection of adjoining planar or curved surfaces. Thus, the projection screen **268** is capable of creating a completely immersive visual environment for a subject being tested on the force measurement assembly **202** because the subject is unable to focus on any particular reference point or line on the screen **268**. As such, the subject becomes completely immersed in the virtual reality scene(s) being projected on the generally hemispherical projection screen **268**, and thus, his or her visual perception can be effectively altered during a test being performed using the balance perturbation system **200** (e.g., a balance test). In order to permit a subject to be substantially circumscribed by the generally hemispherical projection screen **268** on three sides, the bottom of the screen **268** is provided with a semi-circular cutout **278** in the illustrative embodiment. While the generally hemispherical projection screen **268** thoroughly immerses the subject **208** in the virtual reality scene(s), it advantageously does not totally enclose the subject **208**. Totally enclosing the subject **208** could cause him or her to become extremely claustrophobic. Also, the clinician would be unable to observe the subject or patient in a totally enclosed environment. As such, the illustrated embodiment of the balance perturbation system **200** does not utilize a totally enclosed environment, such as a closed, rotating shell, etc. Also, as shown in FIGS. **18-20**, the subject visual display device **207** is not attached to the subject **208**, and it is spaced apart from the force measurement assembly **202** disposed in the base assembly **206**.

In one embodiment of the invention, the generally hemispherical projection screen **268** is formed from a suitable material (e.g., an acrylic, fiberglass, fabric, aluminum, etc.) having a matte gray color. A matte gray color is preferable to a white color because it minimizes the unwanted reflections that can result from the use of a projection screen having a concave shape. Also, in an exemplary embodiment, the projection screen **268** has a diameter of approximately

69 inches and a depth of approximately 40 inches. In other exemplary embodiments, the projection screen **268** has a width lying in the range between approximately sixty-eight (68) inches and approximately ninety-two (92) inches (or between sixty-eight (68) inches and ninety-two (92) inches). For example, including the flange **269**, the projection screen **268** could have a width of approximately seventy-three (73) inches. In some embodiments, the target distance between the subject and the front surface of the projection screen **268** can lie within the range between approximately 25 inches and approximately 40 inches (or between 25 inches and 40 inches). Although, those of ordinary skill in the art will readily appreciate that other suitable dimensions and circumscribing geometries may be utilized for the projection screen **268**, provided that the selected dimensions and circumscribing geometries for the screen **268** are capable of creating an immersive environment for a subject disposed on the force measurement assembly **202** (i.e., the screen **268** of the subject visual display device engages enough of the subject's peripheral vision such that the subject becomes, and remains immersed in the virtual reality scenario). In one or more embodiments, the projection screen **268** fully encompasses the peripheral vision of the subject **208** (e.g., by the coronal plane CP of the subject being approximately aligned with the flange **269** of the projection screen **268** or by the coronal plane CP being disposed inwardly from the flange **269** within the hemispherical confines of the screen **268**). In other words, the output screen **268** of the at least one visual display **207** at least partially circumscribes three sides of a subject **208** (e.g., see FIG. **18**). As shown in FIGS. **18-20**, a top cover is preferably provided over the projector, the mirror, and cutout in the output screen **268** so as to protect these components, and to give the visual display device **207** a more finished appearance.

In a preferred embodiment, the data acquisition/data processing device **204** is configured to convert a two-dimensional (2-D) image, which is configured for display on a conventional two-dimensional screen, into a three-dimensional (3-D) image that is capable of being displayed on the hemispherical output screen **268** without excessive distortion. That is, the data acquisition/data processing device **204** executes a software program that utilizes a projection mapping algorithm to "warp" a flat 2-D rendered projection screen image into a distorted 3-D projection image that approximately matches the curvature of the final projection surface (i.e., the curvature of the hemispherical output screen **268**), which takes into account both the distortion of the lens of the projector and any optical surfaces that are used to facilitate the projection (e.g., generally spherical mirror). In particular, the projection mapping algorithm utilizes a plurality of virtual cameras and projection surfaces (which are modeled based upon the actual projection surfaces) in order to transform the two-dimensional (2-D) images into the requisite three-dimensional (3-D) images. Thus, the projector lens information, the spherical mirror dimensional data, and the hemispherical projection screen **268** dimensional data are entered as inputs into the projection mapping algorithm software. When a human subject is properly positioned in the confines of the hemispherical output screen **268**, he or she will see a representation of the virtual reality scene wrapping around them instead of only seeing a small viewing window in front of him or her. Advantageously, using a software package comprising a projection mapping algorithm enables the system **200** to use previously created 3-D modeled virtual worlds and objects without directly modifying them. Rather, the projection mapping algorithm employed by the software package merely changes the manner in which these 3-D modeled virtual worlds and objects are projected into the subject's viewing area.

Those of ordinary skill in the art will also appreciate that the subject visual display device **207** may utilize other suitable projection means. For example, in an alternative exemplary embodiment, a projector with a fisheye-type lens and no mirror is utilized in the subject visual display system to project an image onto the screen **268**.

In one or more embodiments, the base assembly **206** has a width W_B (see e.g., FIG. **19**) measured in a direction generally parallel to the coronal plane CP of the subject (see e.g., FIG. **18**) and a length L_B (FIG. **19**) measured in a direction generally parallel to the sagittal plane SP of the subject (FIG. **18**). In these one or more embodiments, a width of the output screen **268** of the at least one visual display device **207** is less than approximately 1.5 times the width W_B of the base assembly **206** (or less than 1.5 times the width W_B of the base assembly **206**), and a depth of the output screen **268** of the at least one visual display device **207** is less than the length L_B of the base assembly **206** (FIG. **19**). In the illustrated embodiment, the width of the output screen **268** of the at least one visual display device **207** is greater than the width W_B of the base assembly **206**. In some embodiments, a width of the output screen **268** of the at least one visual display device **207** is greater than approximately 1.3 times the width W_B of the base assembly **206** (or greater than 1.3 times the width W_B of the base assembly **206**).

As illustrated in FIG. **19**, the generally hemispherical projection screen **268** can be supported from a floor surface using a screen support structure **267**. In other words, the screen support structure **267** is used to elevate the projection screen **268** a predetermined distance above the floor of a room. With reference to FIG. **19**, it can be seen that the illustrated screen support structure **267** comprises a lower generally U-shaped member **267***a*, an upper generally U-shaped member **267***b*, and a plurality of vertical members **267***c*, **267***d*. As best shown in FIG. **19**, the two vertical members **267***c*, **267***d* are disposed on opposite sides of the screen **268**. The screen support structure **267** maintains the projection screen **268** in a stationary position. As such, the position of the projection screen **268** is generally fixed relative to the base assembly **206**.

Next, referring again to FIG. **18**, the operator visual display device **230** of the balance perturbation system **200** will be described in more particularity. In the illustrated embodiment, the operator visual display device **230** is in the form of a flat panel monitor. Those of ordinary skill in the art will readily appreciate that various types of flat panel monitors having various types of data transmission cables **240** may be used to operatively couple the operator visual display device **230** to the data acquisition/data processing device **204**. For example, the flat panel monitor employed may utilize a video graphics array (VGA) cable, a digital visual interface (DVI or DVI-D) cable, a high-definition multimedia interface (HDMI or Mini-HDMI) cable, or a DisplayPort digital display interface cable to connect to the data acquisition/data processing device **204**. Alternatively, in other embodiments of the invention, the visual display device **230** can be operatively coupled to the data acquisition/data processing device **204** using wireless data transmission means. Electrical power is supplied to the visual display device **230** using a separate power cord that connects to a building wall receptacle.

Also, as shown in FIG. **18**, the subject visual display device **207** is operatively coupled to the data acquisition/data processing device **204** by means of a data transmission cable **220**. More particularly, the projector of the subject visual display device **207** is operatively connected to the data acquisition/data processing device **204** via the data transmission cable **220**. Like the data transmission cable **240** described above for the operator visual display device **230**, various types of data transmission cables **220** can be used to operatively connect the subject visual display device **207** to the data acquisition/data processing device **204** (e.g., the various types described above).

Those of ordinary skill in the art will appreciate that the visual display device **230** can be embodied in various forms. For example, if the visual display device **230** is in the form of flat screen monitor as illustrated in FIG. **18**, it may comprise a liquid crystal display (i.e., an LCD display), a light-emitting diode display (i.e., an LED display), a plasma display, a projection-type display, or a rear projection-type display. The operator visual display device **230** may also be in the form of a touch pad display. For example, the operator visual display device **230** may comprise multi-touch technology which recognizes two or more contact points simultaneously on the surface of the screen so as to enable users of the device to use two fingers for zooming in/out, rotation, and a two finger tap.

Now, turning to FIG. **25**, it can be seen that the illustrated data acquisition/data processing device **204** (i.e., the operator computing device) of the balance perturbation system **200** includes a microprocessor **204***a* for processing data, memory **204***b* (e.g., random access memory or RAM) for storing data during the processing thereof, and data storage device(s) **204***c*, such as one or more hard drives, compact disk drives, floppy disk drives, flash drives, or any combination thereof. As shown in FIG. **25**, the programmable logic controller (PLC) of the base assembly **206**, the subject visual display device **207**, and the operator visual display device **230** are operatively coupled to the data acquisition/data processing device **204** such that data is capable of being transferred between these devices **204**, **206**, **207**, and **230**. Also, as illustrated in FIG. **25**, a plurality of data input devices **232**, **234** such as the keyboard **232** and mouse **234** shown in FIG. **18**, are operatively coupled to the data acquisition/data processing device **204** so that a user is able to enter data into the data acquisition/data processing device **204**. In some embodiments, the data acquisition/data processing device **204** can be in the form of a desktop computer, while in other embodiments, the data acquisition/data processing device **204** can be embodied as a laptop computer.

Advantageously, the programmable logic controller **272** of the base assembly **206** (see e.g., FIG. **26**, which is a type of data processing device) provides real-time control of the actuator assemblies **258**, **260** that displace the force measurement assembly **202** (i.e., force plate assembly **202**). The real-time control provided by the programmable logic controller **272** ensures that the motion control software regulating the displacement of the force plate assembly **202** operates at the design clock rate, thereby providing fail-safe operation for subject safety. In one embodiment, the programmable logic controller **272** comprises both the motion control software and the input/output management software, which controls the functionality of the input/output (I/O) module of the programmable logic controller **272**. In one embodiment, the programmable logic controller **272** utilizes EtherCAT protocol for enhanced speed capabilities and real-time control.

In one or more embodiments, the input/output (I/O) module of the programmable logic controller **272** allows various accessories to be added to the balance perturbation system **200**. For example, an eye movement tracking system, such as that described by U.S. Pat. Nos. 6,113,237 and 6,152,564 could be operatively connected to the input/output (I/O) module of the programmable logic controller **272**. As another example, a head movement tracking system, which is instrumented with one or more accelerometers, could be operatively connected to the input/output (I/O) module.

FIG. **26** graphically illustrates the acquisition and processing of the load data and the control of the actuator assemblies **258**, **260** carried out by the exemplary balance perturbation system **200**. Initially, as shown in FIG. **26**, a load L is applied to the force measurement assembly **202** by a subject disposed thereon. The load is transmitted from the first and second plate components **210**, **212** to its respective set of pylon-type force transducers or force transducer beams. As described above, in one embodiment of the invention, each plate component **210**, **212** comprises four (4) pylon-type force transducers **254** disposed thereunder. Preferably, these pylon-type force transducers **254** are disposed near respective corners of each plate component **210**, **212**. In a preferred embodiment of the invention, each of the pylon-type force transducers includes a plurality of strain gages wired in one or more Wheatstone bridge configurations, wherein the electrical resistance of each strain gage is altered when the associated portion of the associated pylon-type force transducer undergoes deformation resulting from the load (i.e., forces and/or moments) acting on the first and second plate components **210**, **212**. For each plurality of strain gages disposed on the pylon-type force transducers, the change in the electrical resistance of the strain gages brings about a consequential change in the output voltage of the Wheatstone bridge (i.e., a quantity representative of the load being applied to the measurement surface). Thus, in one embodiment, the four (4) pylon-type force transducers **254** disposed under each plate component **210**, **212** output a total of three (3) analog output voltages (signals). In some embodiments, the three (3) analog output voltages from each plate component **210**, **212** are then transmitted to an analog preamplifier board **270** in the base assembly **206** for preconditioning (i.e., signals S_{FPO1}-S_{FPO6} in FIG. **26**). The preamplifier board is used to increase the magnitudes of the transducer analog output voltages. After which, the analog force plate output signals S_{APO1}-S_{APO6} are transmitted from the analog preamplifier **270** to the programmable logic controller (PLC) **272** of the base assembly **206**. In the programmable logic controller (PLC) **272**, analog force plate output signals S_{APO1}-S_{APO6} are converted into forces, moments, centers of pressure (COP), and/or a center of gravity (COG) for the subject. Then, the forces, moments, centers of pressure (COP), subject center of gravity (COG), and/or sway angle for the subject computed by the programmable logic controller **272** are transmitted to the data acquisition/data processing device **204** (operator computing device **204**) so that they can be utilized in reports displayed to an operator OP. Also, in yet another embodiment, the preamplifier board **270** additionally could be used to convert the analog voltage signals into digital voltage signals (i.e., the preamplifier board **270** could be provided with an analog-to-digital converter). In this embodiment, digital voltage signals would be transmitted to the programmable logic controller (PLC) **272** rather than analog voltage signals.

When the programmable logic controller **272** receives the voltage signals S_{ACO1}-S_{ACO6}, it initially transforms the signals into output forces and/or moments by multiplying the voltage signals S_{ACO1}-S_{ACO6} by a calibration matrix (e.g., F_{Lz}, M_{Lx}, M_{Ly}, F_{Rz}, M_{Rx}, M_{Ry}). After which, the center of pressure for each foot of the subject (i.e., the x and y coordinates of the point of application of the force applied to the measurement surface by each foot) are determined by the programmable logic controller **272**. Referring to FIG. **24**, which depicts a top view of the measurement assembly **202**, it can be seen that the center of pressure coordinates (x_{P_L}, y_{P_L}) for the first plate component **210** are determined in accordance with x and y coordinate axes **242**, **244**. Similarly, the center of pressure coordinates (x_{P_R}, y_{P_R}) for the second plate component **212** are determined in accordance with x and y coordinate axes **246**, **248**. If the force transducer technology described in U.S. Pat. No. 8,544,347 is employed, it is to be understood that the center of pressure coordinates (x_{P_L}, y_{P_L}, x_{P_R}, x_{P_R}) can be computed in the particular manner described in that patent.

As explained above, rather than using a measurement assembly **202** having first and second plate components **210**, **212**, a force measurement assembly in the form of a single force plate may be employed. As discussed hereinbefore, the single force plate comprises a single measurement surface on which both of a subject's feet are placed during testing. As such, rather than computing two sets of center of pressure coordinates (i.e., one for each foot of the subject), the embodiments employing the single force plate compute a single set of overall center of pressure coordinates (x_P, y_P) in accordance with a single set of x and y coordinate axes.

In one exemplary embodiment, the programmable logic controller **272** in the base assembly **206** determines the vertical forces F_{Lz}, F_{Rz} exerted on the surface of the first and second force plates by the feet of the subject and the center of pressure for each foot of the subject, while in another exemplary embodiment, the output forces of the data acquisition/data processing device **204** include all three (3) orthogonal components of the resultant forces acting on the two plate components **210**, **212** (i.e., F_{Lx}, F_{Ly}, F_{Lz}, F_{Rx}, F_{Ry}, F_{Rz}) and all three (3) orthogonal components of the moments acting on the two plate components **210**, **212** (i.e., M_{LX}, M_{Ly}, M_{Lz}, M_{Rx}, M_{Ry}, M_{Rz}). In yet other embodiments of the invention, the output forces and moments of the data acquisition/data processing device **204** can be in the form of other forces and moments as well.

In the illustrated embodiment, the programmable logic controller **272** converts the computed center of pressure (COP) to a center of gravity (COG) for the subject using a Butterworth filter. For example, in one exemplary, non-limiting embodiment, a second-order Butterworth filter with a 0.75 Hz cutoff frequency is used. In addition, the programmable logic controller **272** also computes a sway angle for the subject using a corrected center of gravity (COG') value, wherein the center of gravity (COG) value is corrected to accommodate for the offset position of the subject relative to the origin of the coordinate axes (**242**, **244**, **246**, **248**) of the force plate assembly **202**. For example, the programmable logic controller **272** computes the sway angle for the subject in the following manner:

$$\theta = \sin^{-1}\left(\frac{COG'}{0.55h}\right) - 2.3° \quad (11)$$

where:

θ: sway angle of the subject;

COG': corrected center of gravity of the subject; and

h: height of the center of gravity of the subject.

Now, referring again to the block diagram of FIG. **26**, the manner in which the motion of the force measurement assembly **202** is controlled will be explained. Initially, an operator OP inputs one or more motion commands at the operator computing device **204** (data acquisition/data processing device **204**) by utilizing one of the user input devices **232**, **234**. Once, the one or more motion commands are processed by the operator computing device **204**, the motion command signals are transmitted to the programmable logic controller **272**. Then, after further processing by the programmable logic controller **272**, the motion command signals are transmitted to the actuator control drive **274**. Finally, the actuator control drive **274** transmits the direct-current (DC) motion command signals to the first and second actuator assemblies **258**, **260** so that the force measurement assembly **202**, and the subject disposed thereon, can be displaced in the desired manner. The actuator control drive **274** controls the position, velocity, and torque of each actuator motor.

In order to accurately control the motion of the force measurement assembly **202**, a closed-loop feedback control routine may be utilized by the balance perturbation system **200**. As shown in FIG. **26**, the actuator control drive **274** receives the position, velocity, and torque of each actuator motor from the encoders provided as part of each actuator assembly **258**, **260**. Then, from the actuator control drive **274**, the position, velocity, and torque of each actuator motor is transmitted to the programmable logic controller **272**, wherein the feedback control of the first and second actuator assemblies **258**, **260** is carried out. In addition, as illustrated in FIG. **26**, the position, velocity, and torque of each actuator motor is transmitted from the programmable logic controller **272** to the operator computing device **204** so that it is capable of being used to characterize the movement of the subject on the force measurement assembly **202** (e.g., the motor positional data and/or torque can be used to compute the sway of the subject). Also, the rotational and translational positional data that is received from first and second actuator assemblies **258**, **260** can be transmitted to the operator computing device **204**.

Referring again to FIG. **20**, it can be seen that the base assembly **206** of the force measurement assembly **202** further includes an isolation transformer **276**. In the illustrative embodiment, the building power supply is electrically coupled to the isolation transformer **276**. In one exemplary embodiment, the isolation transformer **276** is a medical-grade isolation transformer that isolates the electrical system of the base assembly **206** from the building electrical system. The isolation transformer **276** greatly minimizes any leakage currents from the building electrical system, which could pose a potential safety hazard to a subject standing on the metallic base assembly **206**. In the illustrative embodiment, the primary winding of the isolation transformer **276** is electrically coupled to the building electrical system, whereas the secondary winding of isolation transformer **276** is electrically coupled to the programmable logic controller **272**.

In the illustrative embodiment, the programmable logic controller **272** may be electrically coupled to the actuator control drive **274** via the emergency stop (E-stop) switch **238** depicted in FIG. **19**. As explained above, in one embodiment, the emergency stop switch **238** is in the form of a red pushbutton that can be easily pressed by a user of the force measurement system **200** (e.g., a subject on the force measurement assembly **202** or an operator) in order to quasi-instantaneously stop the displacement of the force measurement assembly **202**. Because the emergency stop switch **238** is designed to fail open, the emergency stop switch **238** is a fail-safe means of aborting the operations (e.g., the software operations) performed by the programmable logic controller **272**. Thus, even if the programmable logic controller **272** fails, the emergency stop switch **238** will not fail, thereby cutting the power to the actuator control drive **274** so that the force measurement assembly **202** remains stationary (i.e., the brakes on the actuator assemblies **258**, **260** will engage, and thus, prevent any unintentional movement thereof). Also, in one embodiment, the emergency stop switch assembly **238** includes a reset button for re-enabling the operation of the actuator control drive **274** after it is has been shut down by the emergency stop switch.

In the illustrative embodiment, the first and second actuator assemblies **258**, **260** are powered by the actuator control drive **274**. Also, in the illustrative embodiment, the electrical system of the base assembly **206** may further include a power entry module that includes a circuit breaker (e.g., a **20**A circuit breaker) and a filter. In addition, the electrical system of the base assembly **206** may further include an electromagnetic interference (EMI) filter that reduces electrical noise so as to meet the requirements of the Federal Communications Commission (FCC).

Now, the manner in which the programmable logic controller **272** and data acquisition/data processing device **204** of the balance perturbation system **200** are specially programmed to perturb the balance of the subject **208** disposed on the force measurement assembly **202** of the second illustrative embodiment will be described. As explained above, the data acquisition/data processing device **204** is operatively coupled to the programmable logic controller **272** of the force measurement assembly **202**. In one illustrative embodiment, the programmable logic controller **272** (i.e., a data processing device) is specially programmed to generate a first perturbation signal for introducing a first type of perturbation to the force measurement assembly **202** and a second perturbation signal for introducing a second type of perturbation to the force measurement assembly **202**. Also, in the illustrative embodiment, programmable logic controller **272** is specially programmed to control the angular displacement position of the force measurement assembly **202** using the first perturbation signal and the translational displacement position of the force measurement assembly **202** using the second perturbation signal such that the displaceable force measurement assembly **202** perturbs a balance of the person. In other words, the force measurement assembly **202** has two degrees of freedom for the perturbations (i.e., rotation and translation). As described in detail hereinafter, in order to create perturbations, the frequency and the amplitude of the angular and translational displacement positions can be varied. In an alternative illustrative embodiment, the data acquisition/data processing device **204**, rather than the programmable logic controller **272**, may be specially programmed to generate the first and second perturbation signals, to control the angular displacement position of the force measurement assembly **202** using the first perturbation signal, and to control the translational displacement position of the force measurement assembly **202** using the second perturbation signal.

An exemplary angular position signal generated by the programmable logic controller **272** or the data acquisition/data processing device **204** for controlling the angular displacement position of the force measurement assembly **202** is illustrated in the graph **280** of FIG. **27**. As shown in this figure, the y-axis **282** of the graph **280** is the force measurement assembly angle (i.e., force plate angle) in degrees, while the x-axis **284** of the graph **280** is the time in seconds (sec). In the graph **280** of FIG. **27**, it can be seen that the displacement curve **286** oscillates between a minimum angular value of approximately −9.5 degrees and a maximum angular value of approximately 9.5 degrees over a time duration of approximately 10.0 seconds. In FIG. **27**, no perturbations have been applied to the force measurement assembly **202** (i.e., FIG. **27** illustrates the displacement of the force plate without the stochastic perturbation having been applied). In the illustrative embodiment, the force measurement assembly **202** is capable of being rotated between −9.5 degrees and +9.5 degrees (i.e., between a clockwise rotational angle of 9.5 degrees and a counter-clockwise rotational angle of 9.5 degrees).

An exemplary translational position signal generated by the programmable logic controller **272** or the data acquisition/data processing device **204** for controlling the translational displacement position of the force measurement assembly **202** is illustrated in the graph **288** of FIG. **28**. As shown in this figure, the y-axis **290** of the graph **288** is the force measurement assembly translational displacement (i.e., force plate forward/rearward displacement) in millimeters (mm), while the x-axis **292** of the graph **288** is the time in seconds (sec). In the graph **288** of FIG. **28**, it can be seen that the displacement curve **294** oscillates between a minimum translational displacement value of approximately −63.5 millimeters and a maximum angular value of approximately 63.5 millimeters over a time duration of approximately 10.0 seconds. In FIG. **28**, no perturbations have been applied to the force measurement assembly **202** (i.e., FIG. **28** illustrates the displacement of the force plate without the stochastic perturbation having been applied). In the illustrative embodiment, the force measurement assembly **202** is capable of being translationally displaced in both forward and rearward directions by 63.5 millimeters.

In the illustrative embodiment, the first perturbation signal for introducing a first type of perturbation (i.e., angular displacement perturbation) to the force measurement assembly **202** comprises a first stochastic signal, and the second perturbation signal for introducing a second type of perturbation (i.e., translation displacement perturbation) to the force measurement assembly **202** comprises a second stochastic signal. The programmable logic controller **272** or the data acquisition/data processing device **204** is specially programmed to control the angular displacement position of the force measurement assembly **202** using the first perturbation signal and the translational displacement position of the force measurement assembly **202** using the second perturbation signal so as to make the force measurement assembly **202** oscillate in an angular manner, a translational manner, or both an angular and translational manner while the subject **208** is disposed thereon. As will be described hereinafter, the stochastic signal may be of uniform or normal distribution. The stochastic signal is capable of perturbing the subject's somatosensory system while the subject **208** is disposed on the force measurement assembly **202**.

In the illustrative embodiment, the generation of the first and second perturbation signals by the programmable logic controller **272** or the data acquisition/data processing device **204** comprises a plurality of different steps. Initially, by utilizing the input devices **232**, **234** of the data acquisition/data processing device **204** (e.g., the keyboard **232** and/or mouse **234**), a user enters one or more perturbation levels that correspond to at least one of: (i) the stochastic signal base amplitude, and (ii) a frequency of the stochastic signal (i.e., the cut-off frequency of the stochastic signal), and the user additionally may select the type of signal for the stochastic displacement (i.e., uniform or normal). For example, in one exemplary embodiment, a user may have the following six selection options: (i) choosing any one of levels 1 to 10 for the amplitude of the translational perturbation, (ii) choosing any one of levels 1 to 10 for the frequency of the translational perturbation, (iii) selecting the type of signal for the translation perturbation, (iv) choosing any one of levels 1 to 10 for the amplitude of the rotational perturbation, (v) choosing any one of levels 1 to 10 for the frequency of the rotational perturbation, and (vi) selecting the type of signal for the rotational perturbation, In this exemplary embodiment, the first value of the amplitude for both the translational and rotational perturbation is zero (i.e., level 1 corresponds to a zero amplitude, then each of the successive levels may incrementally increase the angle by approximately 1 degree for rotation and approximately 7 millimeters for translation). As such, when level 1 is selected for either of the two amplitudes, the force measurement assembly **202** (i.e., force plate) will not be displaced in that direction. That way, the user is able to customize the displacement of the force measurement assembly **202** such that the force measurement assembly **202** only undergoes rotation, only undergoes translation, or undergoes both rotation and translation. In this exemplary embodiment, the first value of the frequency for both the translational and rotational perturbation may be 1 Hertz, and then each of the successive levels may incrementally increase the frequency by 1 Hertz, up to a maximum frequency of 10 Hertz. In other embodiments, smaller frequency increments may be used for the successive levels, such as 0.1 or 0.2 Hertz.

In the illustrative embodiment, the user may select level 1 through 10 for the amplitude of rotation. The rotational amplitude may range from 0 degrees to 9.5 degrees. The first selected level determines the maximum amplitude of the stochastic signal for the angle of rotation. The user may also select level 1 through 10 for the frequency of rotation. The second selected level determines the maximum frequency of the stochastic signal for angle of rotation. Additionally, in the illustrative embodiment, the user may select the type of signal for stochastic angular displacement (i.e. a uniform or normal stochastic signal). Further, the user may select level 1 through 10 for the amplitude of translation. The translational amplitude may range from 0 millimeters to 63.5 millimeters. The third selected level determines the maximum amplitude of the stochastic signal for the translational displacement. The user may also select level 1 through 10 for the frequency of the translation. The fourth selected level determines the maximum frequency of the stochastic signal for translational displacement. Similar to the angle of rotation, the user also may select the type of signal for stochastic translational displacement (i.e. a uniform or normal stochastic signal). The above selections enable the user to execute the rotational and translational perturbation either independently or simultaneously.

After the user utilizes the input devices **232**, **234** of the data acquisition/data processing device **204** to input the perturbation levels and the signal types, the programmable logic controller **272** or the data acquisition/data processing device **204** generates the uniform or normal stochastic signals based upon the amplitude and frequency values entered by the user. The amplitude values entered by the user determines the upper and lower bounds of the stochastic signals generated by the programmable logic controller **272** or the data acquisition/data processing device **204**, while the cut-off frequency values entered by the user determines the upper frequency limits of the stochastic signals generated by the programmable logic controller **272** or the data acquisition/data processing device **204**. Finally, the programmable logic controller **272** controls the angular displacement and/or translational displacement of the force measurement assembly **202**. Each of these steps will be described in further detail hereinafter. When the programmable logic controller **272** generates the stochastic signals, the amplitudes, the cut-off frequencies, and the signal types of the stochastic signals are transmitted from the data acquisition/data processing device **204** to the programmable logic controller **272** so that the stochastic signals are able to be generated by the programmable logic controller **272**.

Also, in another mode of operation of the illustrative embodiment, the user has the option of entering a sequencing routine for the displaceable force measurement assembly **202**, wherein the rotational and translational displacements are sequenced. In the illustrative embodiment, the sequencing routine allows the user to enter up to 10 signal inputs. For example, one possible sequencing routine could include the following ten displacement tasks executed in a continuous manner while the subject is disposed on the displaceable force measurement assembly **202**: (1) translation displacement, amplitude 3 mm, frequency 5 Hz, and signal type: uniform; (2) translational displacement, amplitude 63.5 mm, frequency 1 Hz, and signal type: normal; (3) rotational displacement, amplitude 8 degrees, frequency 0.4 Hz, and signal type: normal; (4) translational displacement, amplitude 13.5 mm, frequency 3 Hz, and signal type: uniform, (5) rotational displacement, amplitude 5 degrees, frequency 0.5 Hz, and signal type: uniform; (6) rotational displacement, amplitude 1 degree, frequency 1 Hz, and signal type: normal; (7) translation displacement, amplitude 20 mm, frequency 4 Hz, and signal type: uniform; (8) translation displacement, amplitude 5 mm, frequency 5 Hz, and signal type: normal; (9) rotational displacement, amplitude 3 degrees, frequency 2 Hz, signal type: uniform; and (10) translation displacement, amplitude 50 mm, frequency 3 Hz, and signal type: uniform. In this mode of operation, the user would also be prompted to enter a time duration for each of the ten displacement tasks (e.g., 10 seconds for the first task, 6 seconds for the second task, etc.). This exemplary sequencing routine would create a predetermined motion profile of random perturbations for the subject. This type of sequencing routine may be used to increase the difficulty level of the balancing testing for the subject.

In yet another mode of operation of the illustrative embodiment, the user may be permitted to enter a stochastic amplitude value in the range between zero and approximately 9.5 degrees, inclusive (or between zero and 9.5 degrees, inclusive) for the rotational displacement of the force measurement assembly **202**, and between zero and approximately 63.5 millimeters, inclusive (or between zero and 63.5 millimeters, inclusive) for the translational displacement of the force measurement assembly **202**. Similarly, in this mode of operation of the illustrative embodiment, the user may be permitted to enter a cut-off frequency value in the range between zero and approximately 10 Hertz, inclusive (or between zero and 10 Hertz, inclusive) for each of the rotational and translational displacements of the force measurement assembly **202**.

In addition to entering the amplitude, cut-off frequency, and signal type of the stochastic signals for rotational and translational displacement, the user is also able to selectively regulate the beginning and end of the stochastic signals by pressing a graphical start button on the operator display **230** to initiate the stochastic signals, and then by subsequently pressing a graphical stop button on the operator display **230** to end the stochastic signals (i.e., when the display is a touchscreen).

In the illustrative embodiment, the rotational and translational displacements of displaceable force measurement assembly **202** of the balance perturbation system **200** are each capable of being controlled simultaneously and independently. An exemplary normal stochastic signal for rotational displacement that is generated by the programmable logic controller **272** or the data acquisition/data processing device **204** is illustrated in the graph **296** of FIG. **29**. As shown in this figure, the y-axis **298** of the graph **296** is the force measurement assembly angle (i.e., force plate angle) in degrees, while the x-axis **300** of the graph **296** is the time in seconds (sec). In the graph **296** of FIG. **29**, it can be seen that the normal stochastic signal curve **302** oscillates between a minimum lower limit of approximately −8 degrees and a maximum upper limit of approximately 9.5 degrees over a time duration of approximately 10 seconds. As another example, an exemplary normal stochastic signal for translational displacement that is generated by the programmable logic controller **272** or the data acquisition/data processing device **204** is illustrated in the graph **304** of FIG. **30**. As shown in this figure, the y-axis **306** of the graph **304** is the force measurement assembly translational displacement (i.e., force plate forward/rearward displacement) in millimeters, while the x-axis **308** of the graph **304** is the time in seconds (sec). In the graph **304** of FIG. **30**, it can be seen that the normal stochastic signal curve **310** oscillates between a minimum lower limit of approximately −47 millimeters and a maximum upper limit of approximately 58 millimeters over a time duration of approximately 10 seconds.

As yet another example of a perturbation input signal, an exemplary uniform stochastic signal for rotational displacement that is generated by the programmable logic controller **272** or the data acquisition/data processing device **204** is illustrated in the graph **312** of FIG. **31**. As shown in this figure, the y-axis **314** of the graph **312** is the force measurement assembly angle (i.e., force plate angle) in degrees, while the x-axis **316** of the graph **312** is the time in seconds (sec). In the graph **312** of FIG. **31**, it can be seen that the uniform stochastic signal curve **318** oscillates between a minimum lower limit of approximately −9 degrees and a maximum upper limit of approximately 9.2 degrees over a time duration of approximately 10 seconds. As still another example, an exemplary uniform stochastic signal for translational displacement that is generated by the programmable logic controller **272** or the data acquisition/data processing device **204** is illustrated in the graph of FIG. **32**. As shown in this figure, the y-axis **322** of the graph **320** is the force measurement assembly translational displacement (i.e., force plate forward/rearward displacement) in millimeters, while the x-axis **324** of the graph **320** is the time in seconds (sec). In the graph **320** of FIG. **32**, it can be seen that the uniform stochastic signal curve **326** oscillates between a minimum lower limit of approximately −60 millimeters and a maximum upper limit of approximately 62 millimeters over a time duration of approximately 10 seconds.

In the second step of the process, where a random uniform or normal random signal is generated by the programmable logic controller **272** or the data acquisition/data processing device **204** at the selected cut-off frequency, a random number function or subroutine may be used to generate the uniform signal random numbers (e.g., the DRAND function block in a TwinCAT software package). In the illustrative embodiment, the random number function utilized by the programmable logic controller **272** or the data acquisition/data processing device **204** requires an initial value input for the specification of the random number series. The output returns a pseudo-random number in the range −1.0 to 1.0 with double accuracy. That is, the random number function generates the same sequence of random numbers each time that the same seed is utilized. As such, in an exemplary embodiment, the seed value that is used for the random number function is acquired for each trial from the low DW of the system time, which gives a sufficiently random seed for each trial. That way, the programmable logic controller **272** or the data acquisition/data processing device **204** does not generate the same random number sequence or produce any other perturbation trends from trial to trial. In one or more embodiments, the operating system time stamp is a 64-bit integer value, with a precision of 100 nanoseconds (ns), which is updated with every call of the programmable logic controller (PLC) **272**. In one or more embodiments, the low DW (timeLoDW) is the low-value 4 bytes of the time stamp and it changes very rapidly at rate of 0.01 milliseconds (ms). The random signal has a varying frequency. The randomness of the stochastic signal is highly advantageous because the subjects being tested on the displaceable force measurement assembly **202** are not able to as easily learn how to overcome a particular perturbation sequence during a testing or training routine. If the perturbation employed was always the same, then eventually subjects would learn how to adapt to the perturbation, and the training would become less effective.

When the user selects a uniform-type stochastic signal, a respective uniform stochastic signal, such as that depicted in FIGS. **31** and **32**, is used for controlling a respective one of the rotational and translational displacements of the force measurement assembly **202**. However, if the user alternatively selects a normal-type stochastic signal, as described above, two (2) uniform signals U**1** and U**2** generated using the random number function are converted into normal signal N using the following Box-Muller transform equation:

$$N=\sqrt{-2\ln U1}\cos(2\pi U2) \tag{12}$$

In the second illustrative embodiment, as described above for the first illustrative embodiment, the uniform or normal signal is then passed through a fourth order low pass Butterworth filter to limit the frequency component of the signal at a user specified value (i.e., at the frequency entered by the user).

In the illustrative embodiment, prior to the third step of the process, where the programmable logic controller **272** or the data acquisition/data processing device **204** regulates the angular displacement and/or translational displacement of the force measurement assembly **202**, the filtered signal is multiplied by the user-specified amplitude value so as to generate the stochastic signals for controlling the angular and/or translational displacements. When the uniform-type stochastic signal is selected by the user, the uniform stochastic signal for controlling the angular and/or translational displacements are determined by the programmable logic controller **272** or the data acquisition/data processing device **204** in accordance with the following equation:

$$\text{Uniform stochastic signal}=\text{filtered uniform signal}*\text{Amplitude} \tag{13}$$

Thus, in accordance with equation (13) above, the uniform stochastic signal is a function of the filtered, randomly-generated uniform signal and the user-specified amplitude value. More specifically, the programmable logic controller **272** or the data acquisition/data processing device **204** determines the uniform stochastic signal by computing the multiplicative product between the filtered uniform signal and the user-specified amplitude value. Alternatively, when the normal-type stochastic signal is selected by the user, the normal stochastic signal for controlling the angular and/or translational displacements is determined by the programmable logic controller **272** or the data acquisition/data processing device **204** in accordance with the following equation:

$$\text{Normal stochastic signal} = \text{filtered normal signal} * \text{Amplitude}/3 \quad (14)$$

Thus, in accordance with equation (14) above, the normal stochastic signal is a function of the filtered, normalized randomly-generated uniform signal and the user-specified amplitude value. More specifically, the programmable logic controller **272** or the data acquisition/data processing device **204** determines the normal stochastic signal by computing the multiplicative product between the filtered normal signal and one-third of the user-specified amplitude value.

In one or more embodiments, the aforedescribed rotational and translational displacement calculations are specially programmed on an embedded computer (e.g., the programmable logic controller **272** or the data acquisition/data processing device **204**) that provides a deterministic program cycle time of 1 milliseconds (ms). In other words, the displacement update rate of 1 kilohertz (kHz) is guaranteed by either the hardware architecture of the embedded computer or a real-time operating system (e.g., firmware) that runs on it. In these one or more embodiments, the updated displacements are sent to a servo controller (i.e., actuator control drive **274**), which controls the displacements with a closed-loop rate of 4 kilohertz (kHz). In these one or more embodiments, the firmware of the balance perturbation system **200** controls the force measurement assembly perturbations.

In the illustrative embodiment, the programmable logic controller **272** or the data acquisition/data processing device **204** may be specially programmed so as to enable the displaceable force measurement assembly **202** to be controlled in three different modes: (i) rotational displacement only, (ii) translational displacement only, and (iii) simultaneous rotational and translational displacement. In the simultaneous rotational and translational displacement mode, the programmable logic controller **272** or the data acquisition/data processing device **204** utilizes a first stochastic signal to control the rotational displacement of the force measurement assembly **202**, and a second stochastic signal to control the translational displacement of the force measurement assembly **202**. In the independent rotational displacement or translational displacement modes, the programmable logic controller **272** or the data acquisition/data processing device **204** utilizes a single stochastic signal to either control the rotational or translational displacement of the force measurement assembly **202**. Similar to that described above in the first embodiment, the amplitudes of the stochastic signals used to control the rotational displacement and translational displacement of the force measurement assembly **202** are randomly changing over time (i.e., the amplitudes consistently change over time in a random manner). Similarly, the frequencies of the stochastic signals used to control the rotational displacement and translational displacement of the force measurement assembly **202** randomly change over time (i.e., the frequencies consistently changes over time in a random manner). Thus, advantageously, the programmable logic controller **272** or the data acquisition/data processing device **204** generates stochastic signals with both randomly varying amplitudes and frequencies that results in a random perturbation being delivered to the subject **208** on the force measurement assembly **202**. The manner of delivery of the perturbation to the subject **208** on the force measurement assembly **202** is not just random, but rather the stochastic signal itself controlling the perturbation has both random amplitude and frequency content. Advantageously, the displacement of the force measurement assembly **202** does not have a consistent or repeating pattern that can be learned by the subject **208** over time. The stochastic signal generated by the programmable logic controller **272** or the data acquisition/data processing device **204** significantly changes the functionality of the force measurement assembly **202** by enabling the force measurement assembly **202** to simulate unexpected, real-life scenarios that could be encountered by the subject **208**, such as events suddenly disrupting the subject's normal balance. As such, controlling the force measurement assembly **202** using the stochastic signal enables the force measurement assembly **202** to model real-life conditions encountered by the subject **208** so that the testing and/or training of the subject **208** using the force measurement assembly **202** may be greatly enhanced.

It is readily apparent from the above detailed description that the gait perturbation system **100** and balance perturbation system **200** significantly advance the field of human balance assessment and human gait analysis. For example, the gait perturbation system **100** is capable of simulating real-life conditions by subjecting the person being tested to dynamic instability by controlling the treadmill belt speed based upon the stochastic signal generated by the programmable logic controller **25** or the data acquisition/data processing device **28**. Similarly, the balance perturbation system **200** is capable of simulating real-life conditions by subjecting the person being tested to random instability by controlling the displacement of the force measurement assembly **202** based upon the stochastic signal generated by the programmable logic controller **272** or the data acquisition/data processing device **204**. As another example, the aforedescribed gait perturbation system **100** and balance perturbation system **200** are capable of generating random stimuli (e.g., randomly regulating the treadmill belt speed or the force plate displacement) in order to emulate real-life conditions encountered by the person undergoing testing. As yet another example, the gait perturbation system **100** and balance perturbation system **200** described above are capable of more effectively training a person with a gait disorder by delivering random stimuli (e.g., randomly regulating the treadmill belt speed or the force plate displacement) to the person so that he or she is able to more effectively react to unpredictable disturbances that are encountered in real-life scenarios.

Any of the features or attributes of the above described embodiments and variations can be used in combination with any of the other features and attributes of the above described embodiments and variations as desired. Also, the compound conjunction "and/or" is used throughout this disclosure to mean one or the other, or both.

Although the invention has been shown and described with respect to a certain embodiment or embodiments, it is apparent that this invention can be embodied in many different forms and that many other modifications and variations are possible without departing from the spirit and scope of this invention.

Moreover, while exemplary embodiments have been described herein, one of ordinary skill in the art will readily appreciate that the exemplary embodiments set forth above are merely illustrative in nature and should not be construed as to limit the claims in any manner. Rather, the scope of the invention is defined only by the appended claims and their equivalents, and not, by the preceding description.

The invention claimed is:

1. A balance and/or gait perturbation system comprising, in combination:

a balance and/or gait perturbation device configured to receive a person thereon, the balance and/or gait perturbation device including:

one or more displaceable components configured to be displaced at a plurality of different positions, the one or more displaceable components having one or more surfaces for receiving one or more respective limbs of the person; and

one or more first actuators coupled to the one or more displaceable components, the one or more first actuators configured to adjust the displacement position of the one or more displaceable components, the one or more first actuators being primary means for displacing the one or more displaceable components; and

a data processing device operatively coupled to the one or more first actuators, the data processing device configured to generate a stochastic signal for introducing a perturbation to the one or more displaceable components, the data processing device further configured to control the displacement position of the one or more displaceable components using the stochastic signal such that the one or more displaceable components perturb a balance and/or gait of the person.

2. The balance and/or gait perturbation system according to claim **1**, wherein the balance and/or gait perturbation device comprises a force measurement assembly, and the one or more displaceable components comprise a displaceable force plate subassembly of the force measurement assembly; and

wherein the one or more first actuators are configured to adjust the displacement position of the displaceable force plate subassembly.

3. The balance and/or gait perturbation system according to claim **2**, wherein the displaceable force plate subassembly includes at least one force transducer, the at least one force transducer configured to sense one or more measured quantities and output one or more measurement signals that are representative of one or more loads being applied to the one or more surfaces of the displaceable force plate subassembly by the person.

4. The balance and/or gait perturbation system according to claim **2**, wherein the balance and/or gait perturbation device further comprises a base assembly having a stationary portion and a displaceable portion, the displaceable force plate subassembly forming a part of the displaceable portion of the base assembly, the one or more first actuators configured to rotate the displaceable force plate subassembly relative to the stationary portion of the base assembly about a transverse rotational axis disposed above the top surface of the displaceable force plate subassembly.

5. The balance and/or gait perturbation system according to claim **1**, wherein the stochastic signal comprises one of: (i) a uniform stochastic signal and (ii) a normal stochastic signal.

6. The balance and/or gait perturbation system according to claim **1**, further comprising at least one input device, the at least one input device configured to enable a user to input a perturbation level corresponding to at least of: (i) an amplitude of the stochastic signal, and (ii) a frequency of the stochastic signal; and

wherein the data processing device is configured to generate the stochastic signal based upon at least one of: (i) the amplitude of the stochastic signal, and (ii) the frequency of the stochastic signal.

7. The balance and/or gait perturbation system according to claim **6**, wherein the stochastic signal comprises a uniform stochastic signal, the data processing device configured to compute the uniform stochastic signal as a function of a randomly generated uniform signal and the perturbation level input by the user.

8. The balance and/or gait perturbation system according to claim **6**, wherein the stochastic signal comprises a normal stochastic signal, the data processing device configured to compute the normal stochastic signal as a function of a normalized randomly generated uniform signal and the perturbation level input by the user.

9. The balance and/or gait perturbation system according to claim **1**, further comprising secondary means for displacing the one or more displaceable components of the balance and/or gait perturbation device in accordance with a secondary type of displacement that is different from a primary type of displacement of the one or more displaceable components by the one or more first actuators, the secondary means for displacing the one or more displaceable components of the balance and/or gait perturbation device being operatively coupled to the data processing device; and

wherein the data processing device is configured to generate a translational perturbation signal and to output the translational perturbation signal to the secondary means for displacing the one or more displaceable components of the balance and/or gait perturbation device so that the one or more displaceable components of the balance and/or gait perturbation device are displaced in accordance with a translational displacement profile.

10. The balance and/or gait perturbation system according to claim **9**, wherein the secondary means for displacing the one or more displaceable components of the balance and/or gait perturbation device comprise one or more second actuators operatively coupled to the one or more displaceable components.

11. A balance and/or gait perturbation system comprising, in combination:

a balance and/or gait perturbation device configured to receive a person thereon, the balance and/or gait perturbation device including:

one or more displaceable components configured to be displaced at a plurality of different positions, the one or more displaceable components having one or more surfaces for receiving one or more respective limbs of the person;

one or more first actuators coupled to the one or more displaceable components, the one or more first actuators configured to adjust the angular displacement position of the one or more displaceable components; and

one or more second actuators coupled to the one or more displaceable components, the one or more second actuators configured to adjust the translational displacement position of the one or more displaceable components; and

a data processing device operatively coupled to the one or more first actuators and the one or more second actuators, the data processing device configured to generate a first perturbation signal for introducing a first type of perturbation to the one or more displaceable components and a second perturbation signal for introducing a second type of perturbation to the one or more displaceable components, the data processing device further configured to control the angular displacement position of the one or more displaceable components using the first perturbation signal and the translational displacement position of the one or more displaceable components using the second perturbation signal such that the one or more displaceable components perturb a balance and/or gait of the person.

12. The balance and/or gait perturbation system according to claim **11**, wherein the balance and/or gait perturbation device comprises a force measurement assembly, and the one or more displaceable components comprise a displaceable force plate subassembly of the force measurement assembly; and

wherein the one or more first actuators are configured to adjust the angular displacement position of the displaceable force plate subassembly; and

wherein the one or more second actuators are configured to adjust the translational displacement position of the displaceable force plate subassembly.

13. The balance and/or gait perturbation system according to claim **12**, wherein the displaceable force plate subassembly includes at least one force transducer, the at least one force transducer configured to sense one or more measured quantities and output one or more measurement signals that are representative of one or more loads being applied to the one or more surfaces of the displaceable force plate subassembly by the person.

14. The balance and/or gait perturbation system according to claim **12**, wherein the balance and/or gait perturbation device further comprises a base assembly having a stationary portion and a displaceable portion, the displaceable force plate subassembly forming a part of the displaceable portion of the base assembly, the one or more first actuators configured to rotate the displaceable force plate subassembly relative to the stationary portion of the base assembly about a transverse rotational axis disposed above the top surface of the displaceable force plate subassembly, and the one or more second actuators configured to translate the displaceable force plate subassembly relative to the stationary portion of the base assembly.

15. The balance and/or gait perturbation system according to claim **11**, further comprising at least one input device, the at least one input device configured to enable a user to input a perturbation level corresponding to at least of: (i) an amplitude of the first perturbation signal or the second perturbation signal, and (ii) a frequency of the first perturbation signal or the second perturbation signal; and

wherein the data processing device is configured to generate the first perturbation signal or the second perturbation signal based upon at least one of the amplitude or the frequency.

16. The balance and/or gait perturbation system according to claim **11**, wherein at least one of the first perturbation signal and the second perturbation signal generated by the data processing device comprises a stochastic signal.

17. The balance and/or gait perturbation system according to claim **16**, further comprising at least one input device, the at least one input device configured to enable a user to input a perturbation level corresponding to at least of: (i) an amplitude of the stochastic signal, and (ii) a frequency of the stochastic signal; and

wherein the data processing device is configured to generate the stochastic signal based upon at least one of: (i) the amplitude of the stochastic signal, and (ii) the frequency of the stochastic signal.

18. A method for testing and/or training a person using a balance and/or gait perturbation system, the method comprising the steps of:

providing a balance and/or gait perturbation device configured to receive a person thereon, the balance and/or gait perturbation device including:

one or more displaceable components configured to be displaced at a plurality of different positions, the one or more displaceable components having one or more surfaces for receiving one or more respective limbs of the person; and

one or more first actuators coupled to the one or more displaceable components, the one or more first actuators configured to adjust the displacement position of the one or more displaceable components; and

providing a data processing device operatively coupled to the one or more first actuators, the data processing device configured to generate a stochastic signal for introducing a perturbation to the one or more displaceable components, the data processing device further configured to control the displacement position of the one or more displaceable components using the stochastic signal such that the one or more displaceable components perturb a balance and/or gait of the person;

positioning the person on one or more respective surfaces of the one or more displaceable components of the balance and/or gait perturbation device;

generating, by using the data processing device, a stochastic signal for introducing a perturbation to the one or more displaceable components of the balance and/or gait perturbation device;

controlling, by using the data processing device, the displacement position of the one or more displaceable components of the balance and/or gait perturbation device using the stochastic signal; and

displacing, by using the one or more first actuators, the one or more displaceable components of the balance and/or gait perturbation device to the displacement position determined using the stochastic signal such that the one or more displaceable components randomly perturb a balance and/or gait of the person.

19. The method according to claim **18**, further comprising the steps of:

providing at least one input device operatively coupled to the data processing device, the at least one input device configured to enable a user to input a perturbation level corresponding to at least of: (i) an amplitude of the stochastic signal, and (ii) a frequency of the stochastic signal; and

generating, by using the data processing device, the stochastic signal based upon at least one of: (i) the amplitude of the stochastic signal, and (ii) the frequency of the stochastic signal.

20. The method according to claim **18**, wherein the stochastic signal comprises one of: (i) a uniform stochastic signal and (ii) a normal stochastic signal.

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