Materials and Methods

Equipment:

The robotic instrument, Honda Assist, ® was used to analyze the characteristics of the walking patterns of a post-stroke hemiplegic patient and a person with a normal walking ability.

First Subject of Study (A person with a normal walking ability)

The first person subjected to this experiment is a 78-year-old female who does not have a history of a cerebrovascular attack or a neuromuscular disease. She walked down five meters strait while wearing the Honda Assist robotic instrument.

Second Subject of Study (A Post-Stroke Hemiplegic Patient)

The second person subjected to this study was a 72-year-old male who underwent an atherosclerosis, a type of cerebral infarction, at the left hemisphere of his brain in October 2017. He has since suffered from a right-side hemiplegia and resultant walking difficulties. When he was first brought to our nursing-care facility on December 28, 2017, he was in a wheelchair.

Buoyed by the rehabilitation effects of the Honda Walking Assist, however, the male underwent a surprisingly strong improvement in both his walking abilities and degrees of right-left symmetry measured in terms of the Left Scissors Angle (LSA) and the Right Scissors Angle (RSA). He also walked down five meters during the walking ability measurement sessions on May 17, 2018 and on October 8, 2019.

Results

The method for a gate cycle analysis which the authors have selected as the most methodical, useful and verifiable analytical tool is the famous Rancho Los Amigo method.[1)] The outline of the method is explained in Figures 2 and 3. (Please see Pages 118 and 119)

Under this gait phase analysis method, one gate cycle is divided into two half cycles.

At the onset of the first half of the gait cycle at the two persons observed at our study, the front (right) lower limb (extremity) was at the stance phase, while the opposite, left lower limb (extremity) was at the beginning of the swing phase.

The first half cycle is composed of Phase I (approximately 0~10% of the entire gait cycle time passes by the end of this phase) and Phase II (the subsequent 10~50% of the gait cycle time elapses by the end of this phase). The weight of a body is supported by both legs during the Phase I and then by the right leg alone during the Phase II.

During the latter half of the gait cycle, the opposite (left) lower limb (extremity) is at the stance phase, while the front, right lower limb (extremity) goes through the swing phase. The latter half cycle is composed of the Phase III (approximately 50~60% of the entire cycle time elapses by the end of the phase) and the Phase IV (the 60~100% cycle time passes by the end of this phase). The 100 % signifies the completion of a gait cycle.

The weight of an examinee's body is supported by both legs during the Phase III and then by the left leg alone during the Phase IV.

The sequential line graph part of the Figure 2 on Page 118 is the close-up of the area surrounded by a blue dotted-line rectangle in Figure 3 on Page 119, at which the walking pattern of the 78-year-old female is graphically represented with the aid of the HONDA ASSIST®.

The graph's red line shows fluctuations in the measures of angles made with her right femur and the perpendicular drawn from her right greater trochanter. The measures of these angles which are represented as Y-coordinates, or ordinates on the Y-axis, from the graph's origin (0,0) descend or ascend with the passage of time (which are represented as X-coordinates or abscissas on the X-axis).

One gait cycle time makes up 100%. A positive measure of an angle signifies a flexion angle which shows up on the first quadrant, while a negative measure of an angle represents an extension angle, which appears on the fourth quadrant.

Now, let us closely examine the line graph of Figure 3 of Page 119.

In this graph, at the 0% passage of time, or when the examinee began walking, her right heel struck the ground, initiating the rotation over the heel to foot flat to preserve the progression of the body. This moment is expressed as that of the right heel's "initial contact with the ground." At this moment, the measure of angle formed by her right femur and the perpendicular drawn from her right greater trochanter is positive.

At the stage at which the 10% of the gait cycle has passed, which is expressed as the stage of a "Left-Toe-Off," the right leg's single support of her body's weight begins. After the 15% of the gait cycle passed, the measure of the angle formed by the right leg and the perpendicular drawn from the right greater trochanter became zero. This means that the center line of her right femur and the perpendicular overlapped as one straight line.

When about 45% of her gait cycle passed, her right femur attained its maximum extension angle. Then, the measures of her right femur's extension angles started decreasing due chiefly to the forward movement of her pelvis. When about 50% of her gait cycle passed, her left heel struck the ground. Then, a brief phase during which the weight of her body is supported by both legs restarted.

During the latter half of the gait cycle, the left leg assumes and plays the body-weight-supporting duty, which had been assumed and played by the right leg during the first half. The graph portion of Figure 3 shows this normal walking-ability person's gait pattern measured by the electronic angle sensor-equipped Honda Walking Assist.

The red line represents fluctuations in measures of angles formed by her right femur (more precisely, the supposed straight center line of her right femur) and the perpendicular drawn from her right greater trochanter toward the ground.

Meanwhile, the blue line represents fluctuations in the measures of angles formed by the supposed straight center lines of her left femur and the perpendicular drawn from her left greater trochanter towards the ground.

To precisely measure such angles, the Honda Walking Assist projects the measures of angles formed by the two straight lines onto the para-sagittal planes on which the assist's two motors swing forward and backward as if they were a grandfather's old pendulum clock.

The two motors swing the thigh frames forth and back to impart the motor's torque to the right and left thighs through the thigh frames fastened to the legs at a location a bit above the walker's patellas (kneecaps), helping the walker flex or extend her legs.

The measures of angles (ordinates on the Y-axis of the graph drawn in accordance with the Cartesian coordinate system) increase or decrease with the passage of time (which is represented as abscissas on the X-axis of the graph). Whenever readings of measured angles at either femur show up in the minus territory, it signifies that the walker is extending the femur.

At the very beginning of the gait cycle, or at the zero passage of time from the beginning of a gait cycle, which should be expressed as the right heel's initial contact with the ground, the measure of the angle formed by her left femur and the perpendicular drawn from her left greater trochanter is in minus territory, thereby producing a negative reading. (This means that the left femur is at the extension phase).

When the 10% of her gait cycle passes - in other words -- when her left foot is pushed and lifted off of the ground, her left leg starts swinging. After about 15% of her gait cycle passes, she flexes her hip, knee and ankle to advance her left limb forward, creating a clearance of her left foot over the ground. Then, her left femur overtakes the perpendicular drawn from her left greater trochanter towards the ground, with the center of gravity advancing out in front of the supporting right foot.

After this, her left femur accomplishes its maximum flexion angle. Then her pelvis goes on moving forward. This causes her left greater trochanter to move forward as well. After this stage, the measures of angles formed by her left femur and the perpendicular drawn from her left greater trochanter towards the ground starts diminishing. Then, her left heel strikes the ground with some 50% of her gait cycle elapsing from the start of the gait cycle. This brings about the initial contact of the left heel with the ground.

The graph's red line represents fluctuations in the measures of angles formed by the supposed center line of her right femur and the perpendicular drawn from her right greater trochanter towards the ground.

The Honda Walking Assist **projects** the measures of angles formed by the right and left femurs and the perpendiculars drawn from her right and left greater trochanters to the ground **onto the planes** on which the motors swings the thigh frames' rods backward and forward by converting electric energy in the hip frame's batteries into kinetic energy that propels the alloy rods extending downward from the motor modules.

Figure 3 shows the line graph drawn on the basis of the measures of angles formed by the female's right and left legs with two perpendiculars drawn from her greater trochanters (which lie above the hip joints) towards the ground when she walked down the standard distance of five meters in about five seconds.

Figure 3 also attests that the person completed 4 gait cycles during the same span of time (approximately five seconds). Hence, the Right Scissors Angle and the Left Scissors Angle were calculated in accordance with the formulas presented at the bottom of Figure 3.

As described in the lower part of Figure 3, the Right Scissors Angle is defined as the sum of the right leg's maximum flexion angle and the absolute value of the left leg's maximum extension angle.

To cite an example, the table at the middle of Figure 3 attests that the RSA sum of R2 (which stood at 22.3 degrees) and L2 (which came to minus 8.6 degrees) amounted to 30.9 degrees because the absolute value of minus 8.6 is plus 8.6. Still, we had to express the formula to obtain the sum as (R2 minus L2) in view of the fact that the measured L2 value was in minus territory.

Similarly, the Left Scissors Angle is the sum of the left leg's maximum flexion angle and the absolute value of the right leg's maximum extension angle. In other words, the formula for obtaining the sum had to be expressed as L1-R1 (L1 minus R1), when she made the first LSA during her rehabilitation trial session.

As shown at the bottom of Figure 3, the average Right Scissors Angle computed in accordance with the above-mentioned formula came to 30.9 degrees. And the average Left Scissors Angle calculated in accordance with the formula came to 30.35 degrees. In order to obtain a degree of left-right symmetry, the authors divided the 30.35 by the 30.9, obtaining 0.99 as the reading of her left-right symmetry degree.

Figure 2. Healthy Walking-Ability Person's Gait cycle measured by HONDA ASSIST (measured on 2018/8/2)

Observational Gate analysis by Rancho Los Amigo

First half cycle		Latter half cycle	
Front (right) lower extremity plays main role		Opposite (Left) lower extremity plays main role	
Phase I 0~10%	Phase II 10~50%	Phase III 50~60%	Phase IV 60~100%
Both legs' support	Single (right) leg 's support	Both legs' support	Single (left) leg 's support
	Right Stance Phase		*Right SwingPhase*
	Left Swing Phase		Left Stance Phase

Graph of changes in included angle (°) between examinee's femurs and perpendiculars drawn from her greater trochanters to the ground (Graph below is the closeup of the part of her gate cycle pattern surrounded by blue dotted-line rectangle of Fig.3)

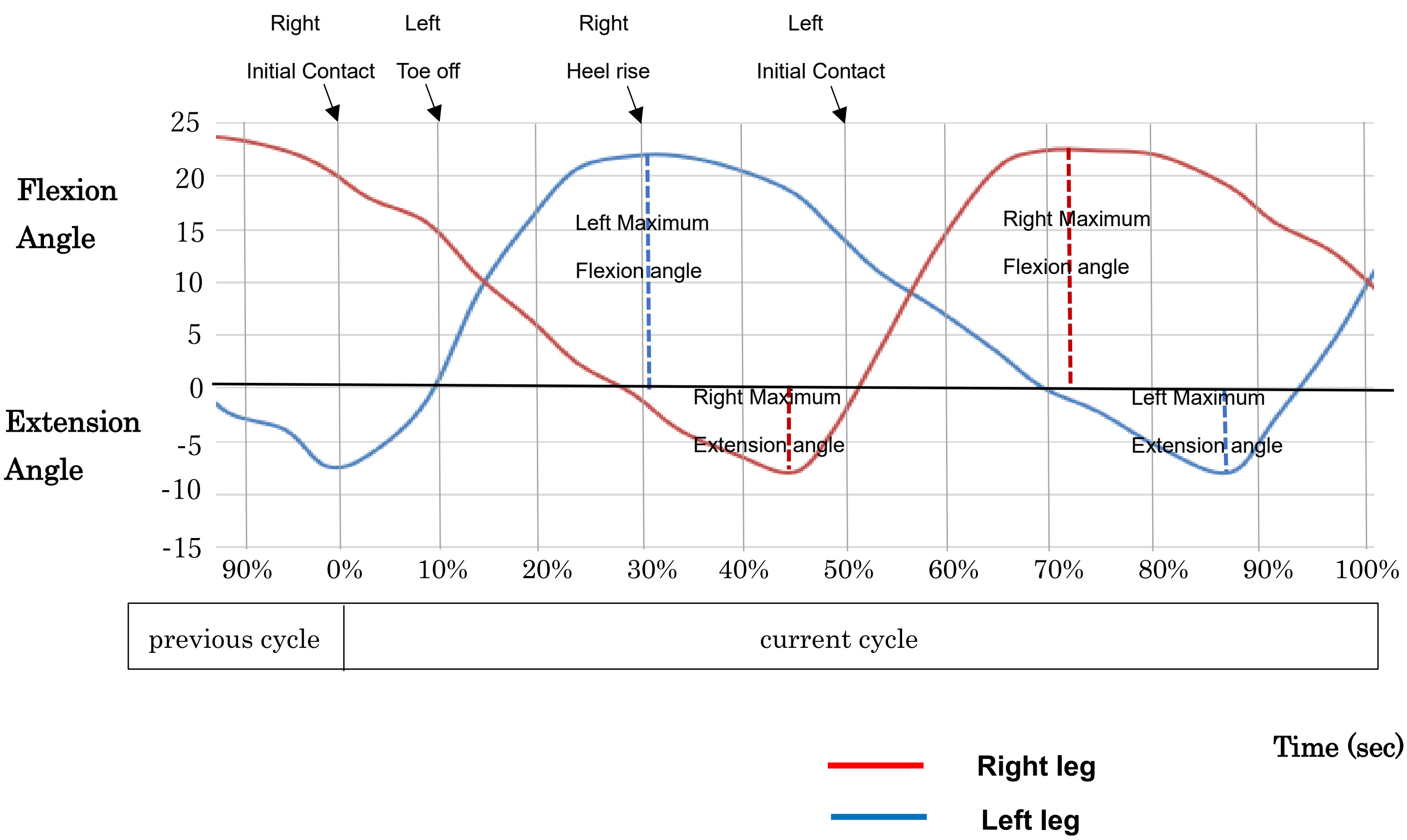

Figure 3. Healthy walking-ability person's Walk Pattern measured on 2018/8/2 and the Definitions of Left and Right Scissors Angles (The close-up of the graph portion for L4~L6 and for R4~R6 are given in Figure 2)

Changes in the angle made with each leg measured with the passage of time

Angle (°)

L1(21.8)	R2(22.3)	L3(24.1)	R4(23.5)	L5(21.8)	R6(22.3)	L7(22.3)	R8(24.1)
R1(-9.7)	L2(-8.6)	R3(-7.4)	L4(-7.4)	R5(-8.0)	L6(-8.0)	R7(-6.3)	L8(-7.4)

How to calculate "Scissors Angles" from Maximum Flexion and Extension Angles

L1~L8: Maximum included angles made with left femur and perpendicular drawn to the ground from left greater trochanter that is projected onto the plane of HWA's motor-sensor located above an examinee's left hip joint.

R1~R8: Maximum included angles made with right femur and perpendicular drawn to the ground from right greater trochanter that is projected onto the plane of HWA's motor-sensor that lies above an examinee's right hip joint.

$$\text{Left Scissors Angle} = \frac{(L1\text{-}R1) + (L3\text{-}R3) + (L5\text{-}R5) + (L7\text{-}R7)}{4} = 30.35$$

$$\text{Right Scissors Angle} = \frac{(R2\text{-}L2) + (R4\text{-}L4) + (R6\text{-}L6) + (R8\text{-}L8)}{4} = 30.9$$

Using an angle sensor in the right motor module that transmits its readings to the hip-frame computer which in turn controls the motor's movements, this robotic instrument measures the angle made by the supposed center line of an examinee's right femur and the perpendicular dropped from his right greater trochanter toward the ground after the two straight lines are projected onto the plane on which the right-side motor moves the thigh frame's rod forwards and backwards.

This plane is a para-sagittal plane incorporating the right greater trochanter. The projection has the aim of enabling the computer to flex or extend the right thigh frame in accordance with the measures of the angles between the right femur and the perpendicular logged at each moment.

Likewise, the left motor's angle sensor measures the angle made by the supposed center line of the left femur and the perpendicular dropped from the left greater trochanter to the ground after the two straight lines are projected onto the plane on which the left-side motor moves the left thigh frame's rod back and forth.

This plane is also a para-sagittal plane incorporating the left greater trochanter. The projection has the aim of enabling the computer to move the left thigh frame in accordance with the measures of the angles between the left femur and the perpendicular logged at each moment.

Right Scissors Angles (RSAs) and Left Scissors Angles (LSAs) thus measured on the para-sagittal planes on which the two motors move the thigh frames are identical to the measures of RSAs and LSAs actually made with each femur and each perpendicular dropped from their respective greater trochanter to the ground.

Therefore, the authors analyzed changes in these projected Right Scissors Angles and these Left Scissors Angles on the para-sagittal planes, which are identical to the measures of angles made by each of the two femurs and each of the its two perpendiculars drawn from the corresponding greater trochanter before and after administering rehabilitation training to poststroke hemiplegic patients for long periods.

In computing the measures of RSAs, the right maximum flexion angle was added to the left maximum extension angle. In computing the measures of LSAs meanwhile, the left maximum flexion angle was added to the right maximum extension angle in accordance with our already-explained principles. In actuality, the measures of the two types of angles were added after they were projected onto the two para-sagittal planes incorporating each of the right and left motor modules.

When a walker advances with either one of his right or left foot acting as the pivot point, each of his left and right greater trochanters describes an arch-like trajectory as if the two hip-joint points were orbiting around their respective pivot points.

These orbiting movements result in the forward advancement of the walker's swinging-side leg -- be it a right or left leg -- as well as the forward advancement of his pelvis and body. These orbit movements are presented, graphically expressed and explained in the Figure 4.

Figure 4 shows the trajectories of the right and left greater trochanters during the first half of a walker's gait cycle when the walker progressed forward from the left to the right on our rehabilitation center' floor in front of an observer who was at the walker's right-hand side.

The upper red illustration shows the trajectory described by the walker's right greater trochanter projected onto his right-side para-sagittal plane.

If we observe how the right greater trochanter moves on the plane while his right heel acts as the pivot of the supporting right leg, we can confirm that the right greater trochanter describes **an arc-like trajectory which would be drawn by the top bob-point of a supposed inverted pendulum.**

During this period, the walker swings his left leg from its extended positions (or from behind) with his body's center of mass advancing in front of the supporting right leg. During this phase, **his right shank rotates forward over the supporting foot**. This maintains the forward progression of his gait.

The lower blue illustration of Figure 4 shows the trajectory described by the same walker's left greater trochanter on his left-hand-side para-sagittal plane in sync with the movement of the right greater trochanter during the first half of the gait cycle.

If we carefully track how the left greater trochanter moves on the left-side para-sagittal plane while his right heel acts as the pivot of the supporting right leg, we can confirm that the left greater trochanter also describes **an arc-like trajectory which is three-dimensionally parallel with the arc-like trajectory drawn by the top bob-point of the supposed inverted pendulum movement of the right greater trochanter.**

But in the case of the trajectory described by the left greater trochanter during the first-half of the cycle, we have to note that the pivot point for the left-side arc-like trajectory is at the intersection at which the straight line drawn horizontally from the right foot's knee joint -- which is acting as the pivot point of the right supporting leg -- reaches the left para-sagittal plane.

Figure 4. Trajectory of the Inverted Pendulum

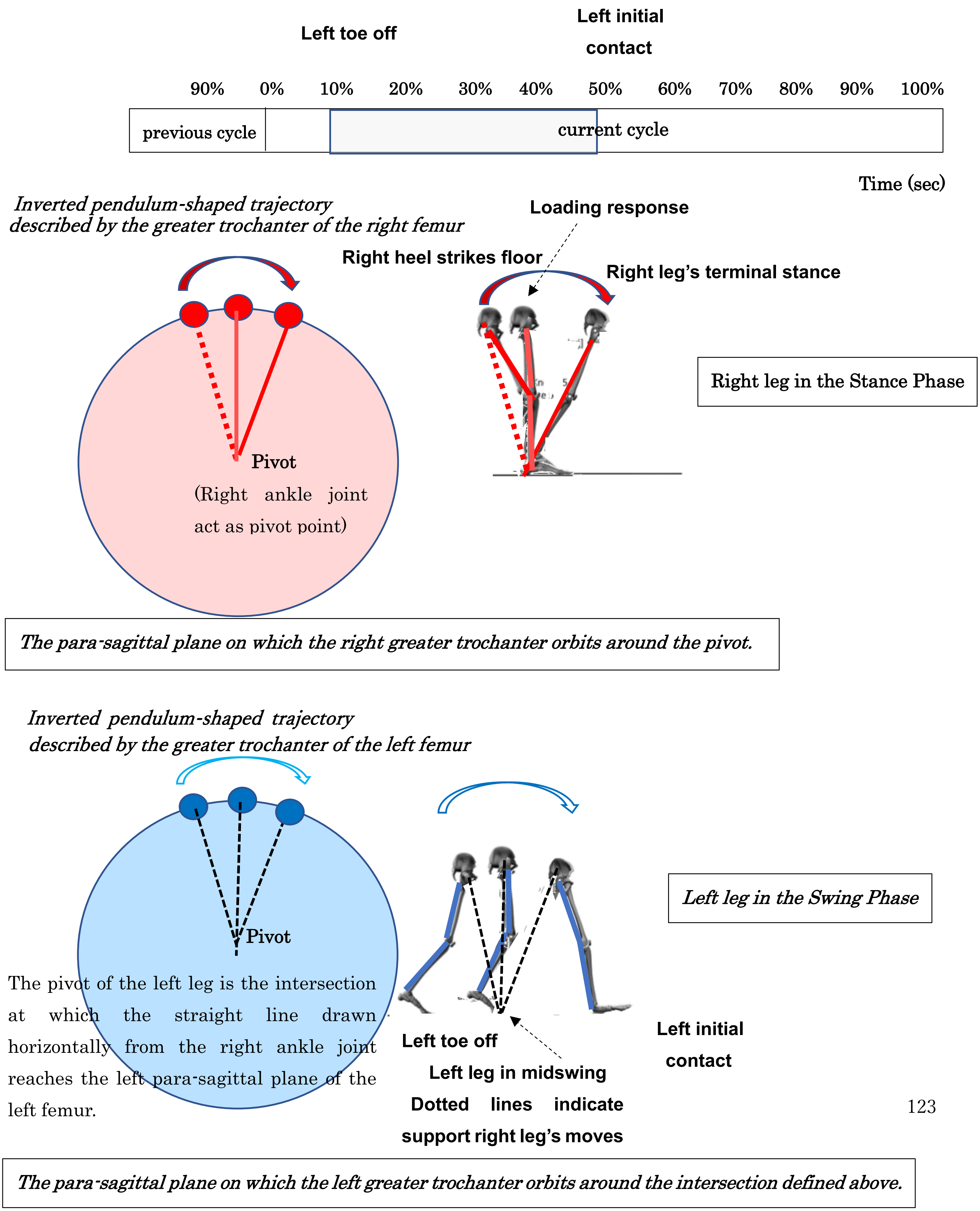

Figure 5. What are Scissors angles ?

What are scissors angles ?　To answer the question, let us now concentrate on the meaning of the Left Scissors Angle (LSA). How can we widen the LSA? The LSA is the sum of the left maximum flexion angle and the right maximum extension angle. The left maximum flexion angle can be widened in cases where the muscles of a person's left thigh that are in charge of flexing the left leg are trained and strengthened through rehabilitation sessions.　Meanwhile, the right maximum extension angle can be widened when the muscles of his left lower limb are trained and enhanced so that it can support the body's weight strongly while the person may extend his right leg as far as possible.

The sum of those two maximum measures of angles depend on the robustness and stability of the muscles of his left leg, including those of the muscles of his carf (technically, the medial and lateral heads of his Gastroenemius) as well as the strength of his quadriceps at his left fermur, including the rectus femoris, and that of the semitendinosus of high right femur.

While these and other factors are taken into the accounts, the LSA has been defined with the following formula and drawings presented below.

Left scissors angle = Left maximum flexion angle (A2)+ Right maximum extension angle (B2)

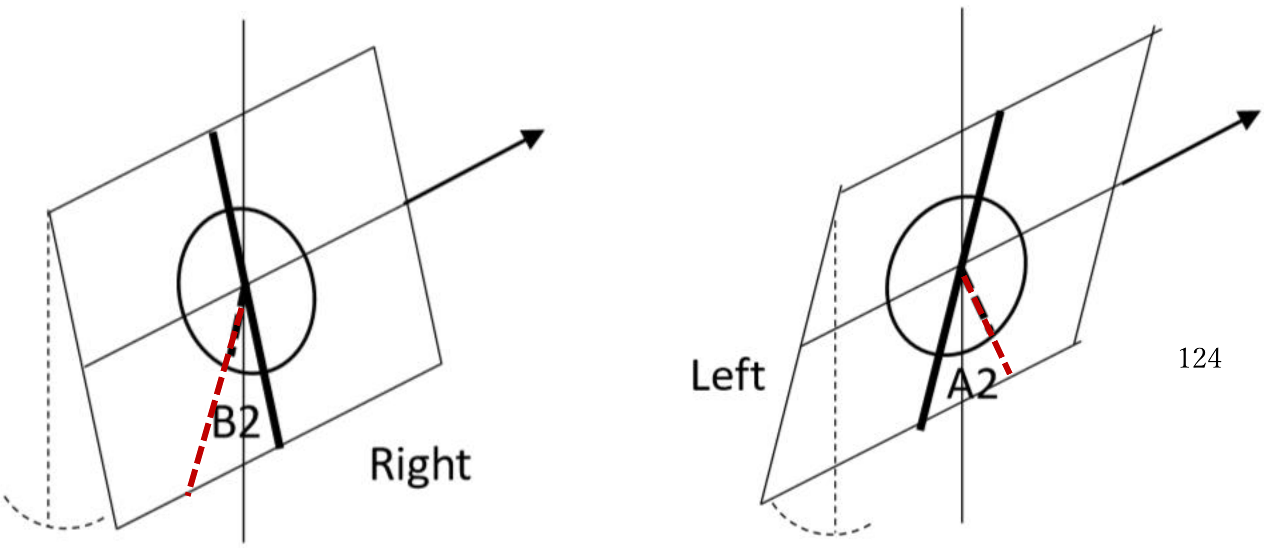

Figure 5 and the definitions of the LSA and RSA in this paper's abstract provide a clear idea of "scissors angles."

It needs to be comprehended that the LSA and RSA go on changing at each moment of a walker's gait cycle.

The measures of the two types of angles are computed by adding the two measures which continuously change in accordance with three factors -- (1) the passage of time from the moment of the start of a walker's movement, (2) the whereabouts of para-sagittal planes on which the measures are calculated by the angle sensor of the Honda Walking Assist and with (3) continuously-changing phases of the walker's gait cycle.

(1) The passage of time: As exemplified by the graph portion of Figure 2 on Page 118, the left maximum flexion angle was formed before the right maximum extension angle was made in the case of the 78-year-old female subjected to this study.

Which angle is made first depends on which leg a walker starts flexing at the start of a rehabilitation session or a walk-trial session and on what phase the walker begins the rehabilitation session at.

(2) The whereabouts of para-sagittal plane: A measure of angle formed by the left femur and the perpendicular drawn down from the left greater trochanter to the ground is present on the left side para-sagittal plane, while a measure of angle formed by the right femur and the perpendicular drawn down from the greater trochanter of the right femur to the ground is present on the right-side para-sagittal plane.

The two measures of angle on the different para-sagittal planes are measured and added by the Honda Walking Assist.

(3) Phases of a walker's gait cycle: The left maximum flexion angle of a walker's left leg is made around the time when the walker completes the swing of his left leg, while he pushes his right heel on the ground, thus

creating its clearance from the ground.

And the right maximum extension angle of his right leg is formed around the time when the walker extends his right leg the most with his center of gravity advancing out in front of his right supporting leg.

Around this moment, the right heel raises from the ground as he rolls onto the ball of his foot. Around this moment, his left foot is positioned for its initial foot contact with the ground.

Consequently, the measures of the two types of scissors angles are computed by adding the two measures of angles which continuously change in accordance with the three factors.

Still, the authors have concluded that the RSA and LSA measured by this robotic instrument universally act as accurate indicators of humans' gait ability and therefore can help doctors and therapists around the world to quantify, record, understand and analyze the characteristics of the gait cycles at both post-stroke hemiplegic patients and persons with healthy walking ability.

We have concluded that this robotic instrument is universally useful in measuring, quantifying, evaluating and analyzing the gait ability of post-stroke hemiplegic patients and healthy persons with normal walking ability.

Our most important conclusion is that the robotic instrument is useful in facilitating the rehabilitation of post-stroke hemiplegic patients' walking ability.

The Application of Scissors Angles to the evaluation of post-stroke hemiplegic patients' walking ability and their gait cycle characteristics

Data on the degrees of left-right symmetry based on data on the Right Scissors Angles and Left Scissors Angles collected by the Honda Walking Assist with its measurements and quantification of the gait characteristics of both post-stroke patients and persons with normal walking abilities must be computed in accordance with the following formulae as shown in the following Table 1.

Table 1. Mathematical Formulae used in Computing Degrees of Symmetry between "Right Scissors　Angle" (R) and "Left Scissors　Angle" (L)

Condition	Formula for computing	Criteria to determine which formula should be used to calculate degrees of symmetry between the right scissor's angle (R) and the left scissor's angles (L)
R > L	L/R	Formula used in cases where right leg's walking function is superior to paralyzed left leg's
R = L	1	In cases where L and R are the same disregards of whichever foot is swung forward to the widest angle from perpendicular drawn from a person's hip joint to the ground
R < L	R/ L	Formula used in cases where left leg's walking function is superior to paralyzed right leg's

When there is no difference in the walking abilities of a patient's right and left leg, his right scissors angle is identical to his left scissors angle. That means R=L. In cases where there is a laterality in the two legs' walking functions, a smaller measure of scissors angle must be divided by a larger measure of scissors angle. Therefore, measures of the degrees of left-right symmetry produce readings below 1. In other words, if a value computed in accordance with the table's formulae is below 1, it means that there is a laterality in the walking abilities of the left and right legs at the observed.

In the routine practice of rehabilitation medicine, all patients can be considered to be individual valid cases by himself. Usually, it is not possible to find an object or objects of comparison for each ailing individual. Usually, the only rational way to set up an object of comparison is to compare data taken from the same individual historically on different days – as time goes by.

However, in cases of post-stroke hemiplegic patients, one body can be legitimately and scientifically divided into comparable halves for the halves' performance comparison purpose. While one side of the patient's body is paralytic, the other side is healthy. If we consider the hemiplegic side as a sort of the entire comparable patient in itself, the other side or the healthy half can be legitimately considered as a medically rational object of comparison.

The Honda Walking Assist can accurately measure, quantify and record the characteristics of the walking patterns of the same patient's right land left legs separately and thus compute the measures of RSA and LSA respectively.

The right and left scissors angles and their degrees of symmetry thus obtained enable us to compare the performance and characteristics of the gait phases of the hemiplegic half and the healthy half. If there is no laterality between the two measures of angles, that means the observed is not hemiplegic. Table 1's mathematical formula would produce the value of 1 or at least readings very close to 1.

In Figure 3 of this paper, data taken from the female subject with a normal walking ability was presented. Her right and left scissors angles stood at 30.9 and 30.35, respectively.

Let us apply the first of the three formulae in Table 1 (Page 127) to her case in accordance with the rules of calculation on a degree of right-left symmetry as defined in the table, because her right leg's walking ability is superior to her left leg's.

When we divided the average of her LSA by that of her RSA, we obtained 0.98 as the reading of her right-left degree of symmetry, because 30.35 divided by 30.9 equals 0.98. We concluded that this subject's walking ability should be considered to be within normal limits.