Anatomy of the COP Gait Line and Computer-Aided Gait Analysis

You can quantify these weight-bearing events by using state-of-the-art pressure technology.

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Introduction

In 1984, the UPS man delivered my brand new bundle of joy, a personal/office computer. During its lifespan, we played games, made music, wrote papers, managed patient records and engaged in a lot of data entry. I thought of it as a cross between my buddy and a bank vault. It was then that I learned the importance of two new adages: "Back up your data, then backup your backup" and "To err is human—to really screw up, you need a computer."

Just months before, my research partner was being born in the same town, a few miles away from where I was completing my residency. As we grew up and into our professions, computers advanced in reliability, processor speed, storage and practicality, they became staples in the medical front office. More recently, they are finding their way, in ever- increasing numbers, into treatment rooms as diagnostic tools of the private practitioner, and training and learning devices for the patients. The ability for those of us healthcare practitioners concerned with gait, to have a tool to help us gather and assimilate data on the functioning foot is essential. The knowledge the computers provide allows us to see when, and in what

order, biomechanical events occur based on pressure and movement patterns. The summarized information includes force, and pressure in particular areas. When we add the element of time that force is placed on an area we can then consider more advanced into meaningful information that allows diagnostic considerations and supports individualized treatment protocols. The comprehensive report that is generated can now be used to communicate with the patient and his/her support team, which can in-

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concepts of fatigue, overload, imbalance and shock absorption, as well as parameters such as segmental onset, duration, and peak pressures.

Dr. Segel

Computer-aided gait analysis makes possible the quantification of weight-bearing events by using stateof-the-art pressure technology and examining the ground force reaction to an area over time which it occurs as a person is moving. In turn, this data that is captured can be turned clude family members and other interested healthcare professionals. The benefit of communicating the results via a quantifiable report validates patient concerns and improves compliance to a treatment regimen with both the individual and the support team. It also stands as a permanent record for comparison during or after completion of the care plan.

Presented herein is a foot-centric discussion of the anatomy of one such picture of gait progression *Continued on page 152*

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called the Center of Pressure (COP) line, component parts, their generation, meaning and practical use.

To begin the communication let's first start with the basic math and physics of these matters. If we start with the human body as a bipedal mass making two contacts, or collisions, with the ground, we know that the action of these collisions must generate an equal and opposite reaction which will produce mechanical energy (Figure 1).

The initial collision of our mass and our contact with the ground begins the onset of closed-chain kinetics. Newtonian mechanics reminds us that for every action, such as the colliding of two masses, there will be an equal and opposite reaction that we have to handle. This is the ground reaction force. As the foot is three-dimensional and strikes the ground in a progressive fashion, the ground reaction force has a different vector and magnitude, millisecond to millisecond.

All contributions to the instantaneous movement must involve this changing and moving force at the ground contacts (feet), and the forces of our mass above. In order to move forward in synchrony with our body's mass, the parts of the foot with ground contacts must work physically to first adapt to the changing momentum of our mass, then support it all on one limb, and finally advance the other limb, all while



Figure 1: Mass 1 & Flexible Mass 2 > Collision (action) > Newtonian reaction (ground reaction force) > Shock > Mitigation of ground reaction force up the kinematic chain and facilitated shock absorption.

keeping the foot in contact with the ground. Throughout this often-repeated chain of events, the exertion of the changing forces over specific areas is measured as pressure.

Pressure over the ground can be

and spatial data is helpful in illustrating the complete movement and in understanding the way we function and visualize areas of concern.

The center of pressure (COP) gait line is a visual expression of the part of gait during which the foot is in contact with the ground (Figure 2). This is stance phase. It takes into account where all contact pressure points are and what their values are. It is represented by the aggregate of pressure dots which are plotted with respect to time and at a specific sample rate, say 120-300 samples per second. Each dot reflects a center of pressure, or COP point, and is plotted sequentially from the initial contact point, usually at the lateral heel, until the termination of the stance phase of gait, which typically is toe-off.

There are three types of COP gait lines (Figure 3). Type one is generated from tracking a single step,

In the average foot, the COP gait line usually will pass three times through "foot neutral", described as the neutral axis of the foot (a line that bisects the foot).

easily tracked and measured with sensitive pressure sensors. Computer-aided gait analysis units can measure pressure directly based on the changing distributions of force holding and moving our mass. Tracking where the center of pressure falls throughout gait through temporal type two is a series of COP gait lines obtained from recording several gait cycles and type three is a single composite line created from averaging a series of COP gait lines.

When the COP gait line is of sufficient length, one can note that there are areas within the line that may

> be denser than others. This phenomenon speaks to the speed and how quickly the center of pressure is shifting. Portions with greater dot separation are lighter and indicate that there is more forward COP gait line progress over a given time, and the dot deposition is farther apart. This highlights more rapid COP gait line movement than darker, denser, slower regions. This can be verified by Continued on page 153



Figure 2: Single Step COP gait line with marked key events and phases to look for



Figure 3: Three types of COP gait lines: 1) Single Step, 2) Series of consecutive measured COP lines, and 3) Averaged gait line showing dots representing how quickly the center of pressure is shifting.

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viewing the COP gait line using the report or playback mode on some computerized gait analysis systems.

On occasion, the examiner might note a period of time in which the center of pressure does not move forward and instead travels in a retrograde fashion. This can be seen in many forefoot strikers as well as patients with instability, neurologic impairment, initial contact point to the and pain.

COP Gait Line

In the average foot, Typical crossing regions are the COP gait line usual- identified in Figure 2. ly will pass three times

through "foot neutral", described as the neutral axis of the foot (a line that bisects the foot). The typical crossing regions are also identified in Figure 2. The first time is likely to occur at, say, 10% of the overall stance phase, the next, at about 50% and lastly somewhere around 70-75%.

COP gait lines can show us a great deal about foot position, function, motion, instability, impulse, contralateral limb function, biomechanical abnormalities and their likely effects on the kinetic chain (Figure 4). With the definition of stance and the COP gait line in place, the shape and timing can now be investigated to determine more outcomes. The COP gait line is displayed with percent of time in stance phase on one axis and the COP positioning coordinates on the other axis. As stance is a subphase, representing about 60% of the entire gait cycle, the graph axis reflecting time runs from 0% to 100% of stance phase. It's useful to breakdown this 100% into smaller portions for easier digestion. In this case, we'll use contact phase, midstance, and propulsive phases of gait, though there are other models with similar and alternate nomenclature.

Contact Phase

Contact phase is described as

Propulsion Figure 5: Initial contact point center of pressure with medial lateral and neutral zones in case A. exhibiting diminished capacity for local shock absorption and B. a supinated landing

Figure 4: Center of Pressure Gait Line: Aggregate of pressure dots from the termination of stance phase with two to three crossings on the neutral forward axis.



(initial forefoot loading) as described by Root.1 This is also when the contra-lateral foot contacts the ground according to Perry and Winter.2,3 There are two distinct sections of contact phase.

A.

Initial double support starts with contact and ends with contra-lateral toe-off, followed by the initial single support stance, sometimes referred to as the "loading response."

In normal ambulation, the contact phase is subject to initial reaction to the ground as part of initial weight acceptance and it occupies about the first 17-24% of stance phase with



lowed by a frontal plane reaction to that pronation or supination segment which is also, conveniently, used to facilitate shock absorption. This initial COP gait line movement is also usually curvilinear in shape with a magnitude, veloci-

ty, and vector which commonly ends at a point commensurate with the furthest extent of rear foot pronation.

This is how the above components fit together. A lateral heel placement at the initial contact point followed by significant medial motion may indicate a rear foot varus deformity whereas a medial heel placement with little or no deviation on the horizontal plane of the COP gait line may indicate a diminished capacity for local shock absorption. These indications are heavily driven also by the neuromuscular contributions.

If there is limited or diminished muscle activation around the joints, there may be limited or diminished capacity to absorb that shock. The terminal portion of the contact phase, sometimes referred to as the "loading

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20% being the accepted normal value (Figure 5).

The beginning of the COP gait line has several areas of interest to explore because of these requirements for movement during the contact phase. The placement of the initial contact pressure point along the positional axis is our first consideration. A heel that lands in the region designated as "lateral" by the computer-aided gait analysis program indicates a possibly supinated initial contact with the ground whereas a "medial" landing demonstrates a possibly pronated contact with the ground. This initial position is folresponse", is often characterized by a re-supination segment where the muscles have to work against gravity and body weight to stabilize the foot and prepare it to become a lever worthy of propulsion and limb advancement. This re-supinatory phase can be visualized on the COP gait line by finding the final extent of rear foot pronation (if the patient exhibits normal rear foot patterns) and following its lateral motion until this segment stabilizes in midstance marked by a change of direction or more distal directed pattern.

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framework, orientation, and its effect on the motion and force distribution-adequate muscular activity, or lack thereof, contributes to the shape and meaning of the COP gait and validate a powerful rehabilitation program based on this model incorporating muscle activity and understanding. Consider the patient who presents with a virtually straight COP gait line through their contact phase of gait. We would note that

The skilled practitioner can build and validate a powerful rehabilitation program based on this model incorporating muscle activity and understanding.

line as well. When we look back at the contact phase and within it, the first contact response, we often expect to see the initial contact point of the calcaneus on the lateral aspect of the foot's pressure plot. One might also note that the tibialis anterior, a major supinator of the foot, has a peak point that coincides with, and just prior to, that initiation of contact response (Figure 6).

The ensuing motion of the heel is usually one of pronation. Not by coincidence, the COP gait line typically moves in a medial direction with a certain speed and slope. During this period, the tibialis anterior rapidly decreases in activity and allows the foot to pronate and the COP gait line to move in this medial direction (Figure 7). This becomes of particular importance when evaluating less than ideal COP gait lines and their relationship to muscular weakness, dysfunction, laxity, tightness and/or asymmetry.

The skilled practitioner can build



Figure 6: The Contact Phase points and COP gait line events to look for. 1) Is the initial contact point, 2) Is the contact response which is the slope of point 1) ending at 3), which is the end of that contact response and is typically the farthest point of medial contact in the heel.

this patient exhibits a lack of frontal plane motion, which translates to poor shock absorption at the level of the foot and a possibility of significant hyperactivity of the tibialis anterior. We can see this prolonged onset when muscle activity amplitude and shape is known. Surface electromyography direct transmission systems give this insight. This added aspect of methodology could then be applied to all the muscles that effect gait for further insight and targeting treatment.

Pre-Midstance and Midstance

The time between the very first part of forefoot loading and full forefoot and metatarsal loading is sometimes referred to as the beginning portion of midstance, or pre-midstance. Pre-midstance onset range is usually from 7-12% and should end at the latest, 25% of stance. Specific COP gait line patterns of pre-midstance behavior correspond to certain biomechanical foot deformities.

For example, a pes planus foot type tends to show a straighter and slower COP gait line progression in the middle part of the foot during midstance while a likely rigid pes caves foot is likely to be arched and move more rapidly through midstance.

The following portion of midstance may often be referred to as "foot flat phase" in other professional arenas including the National Institute of Health as well as many international organizations. This midstance phase constitutes the middle



tibialis anterior rapidly decreases in activity and allows the foot to pronate and the COP gait line to move in this medial direction. This coincides with the optimal amount of shock absorption.



Figure 8: "Falling arches" with visible medial deviation of the COP gait line.

35-40% of stance phase and ends when the heel lifts off the support surface. Differences in pre-midstance and midstance values directly impact the position with which the forefoot hits the ground. It should also be noted that a rapid and early engagement (shorter midstance of the forefoot with the ground) should have the healthcare practitioner consider a neurological condition such as foot drop.

During midstance, the COP gait line at the middle of the pressure plot should be somewhat arced. We have noted that straightening of this arc has been associated with patients reporting back pain thought to be Continued on page 157



100% of Gait



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the result of a lack of frontal plane motion to absorb shock created by impact and reactive ground forces, but this is just one hypothesis. This is also the segment most affected by "falling arches" with visible medial shift of the COP gait line (Figure 8).

Deviations of the COP gait line due to instability, peripheral neuropathy, and pain are more easily spotted in midstance as well (Figure 9). The important event that occurs is the dividing point between the midstance and propulsive subphases. This dividing point is the point when the heel lifts or heel-off. Ideally, the heel will lift off at 55% of contact phase. Mild to moderate earlier deviations from this timing marker may indicate Achilles tendon or equinus issues whereas delays lifting the heel may indicate instability and an apropulsive gait (Figure 10).

Propulsion

The propulsive subphase of gait begins at heel-off, occupies approximately the last 45% of stance phase and ends when the foot leaves the ground, typically known as toe-off. We can further break this stage down into two sections, when the contralateral limb is in swing phase, and then, when the contralateral limb comes down to begin its contact phase. During these stages the COP gait line deviates from the direction of the body's movement. Perhaps the deviation is occurring because the body's main, flexible mass also tends to shift its mass to the other foot which would likely move the pressure on the stance phase foot to the medial side. This medial movement during propulsion is also, coincidentally, towards the foot that was not in stance phase. Balance is an important factor throughout stance phase, and especially at the very end, during propulsion.

This propulsive portion of the COP gait line should extend through the full range of toe extension which is typically rather straight, but some lines end early or abruptly, without the straightforward angle of roll-off (seen in Figure 11 B). The length of the segment



Figure 10: COP gait lines during the propulsion phase. Similar deviations from the walking direction are displayed but A Exhibits less forefoot pronation in propulsion than B.



Figure 11: COP Angle is the angle between the walking direction and the linear regression line. In this case we see three different shapes with progressively increasing COP angles, the last on the right being the largest and having an almost C shape.

may give clues about the presence of pain or limited range of motion at the first metatarso-phalangeal (MTPJs) joint found in conditions like hallux limitus/rigidus. As an aside, the other way to determine functional hallux limitus (FHL) is to look at hallux and first metatarsal pressure ratios.

When FHL is present that ratio may be 2:1, or double the pressure. The forward speed of the COP gait line in this phase tends to slow down, or linger, over the MTPJs joints. The slope, extent, and velocity of movement in this segment of the gait line typically matches the exact direction of movement and speaks to any varus or valgus deformity present in the forefoot and the performance of the transverse arch. This propulsive segment overall is one of our main considerations when deciding on forefoot posting and metatar-*Continued on page 158*



Figure 9: COP gait line real-time display.



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sal pad application and placement.

Biomechanics during all phases is all about physical events happening at specified times in a specific order. Aside from looking within the subphases of stance phase we can also look at the bigger picture. We also use the pressure distribution map and data to determine deviations from the direction of the COP gait line movement. The overall direction of the COP gait line takes into account the entire COP gait line data set visually and graphically. We can eyeball a new straight line named the COP linear regression line.

In many cases, an angle value is used to denote a relationship between the subject COP gait line and its regression line to give you measures of linear regression; however, the general shape can be qualitatively very useful in recommending footwear that will complement gait instead of causing friction.

COP Gait Lines

COP gait lines that show larger curves away from the COP linear regression line (creating more area) could quite possibly suggest that patients would be most comfortable or perform more optimally in a curved or semi-curved-lasted shoe, whereas fewer and smaller differences might suggest a straight or combination-lasted shoe for improved gait. These correlations are under heavy objective observation in the field and with these computer-aided gait analysis tools, the investigations are accelerated.

To summarize the goal of the overall COP gait line progression we can look back to the requirements for ambulation. They include accepting our mass, supporting it all on one limb, then advancing the other limb, all while keeping contact with the ground. By noting the location, speed, and shape of the COP gait lines we gain objective pictures of how well patients' contacts with the ground are providing a stable base of support in stance phase, allowing forward progression of their mass over the ground contacts, maintaining minimum energy expenditure,

and lastly, employing appropriate mechanisms for shock absorption and dissipation of forces. With this information we can help.

There is a lot of data put forth and incorporated for uses like these, and you may wonder what the real advantages and procedures are. This is discussed and broken down even more in our next body of work dissecting the computer aided gait analysis temporal and spatial parameters. There are needs to understand, find meaning and application in the data, and implement the business advantage in all of these reproducible objectifications. Then there is also the need to expand one's professional identity, and relevance has never been more important than in this rapidly-changing medical landscape.

Being known for the procedures we perform may be useful in some circles but may also be quite limiting overall. Demonstrating prowess in gait analysis and being able to use computer-aided gait analysis in treatment plans and diagnosis are increasingly appreciated and required skill sets, not only to the patient and primary care physicians, but also orthopedic surgeons, chiropractors, physical therapists, neurologists and pedorthists. As many of these specialists refer to gait parameters differently, we chose to lay out the common biophysics and biomechanics, put forth a workable cross-platform model, and reconcile the nomenclature. This standardization allows for a more cooperative environment among healthcare practitioners, assists in supplier communication and improves patient outcomes.

With a second, even older adage in mind-that a picture is worth a thousand words-computers can create a summary of gait by charting the progression of motion and force distributions. The picture then becomes an assimilation of hard data used as a ready reference for comparative walking. We can use computer-aided gait analysis to generate normal, baseline and after-treatment models to answer the increasing demands of evidence-based medicine. Changes in patterns are an efficient means of comparison, outcomes, direction, and documentation of improved patient outcomes. PM

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