



Figure 19. A dress code guide

5 Results overview – Running module

The Running module has three main results pages, Running Performance, Gait Characteristics and Joint Loading. These pages will be described below.

5.1 Running Performance page

The first page that appears after a test has been completed is the Running Performance page (see Figure 20). This page is fully dedicated to mechanical running efficiency and the stride parameters associated with it. In Figure 21, we present a quick interpretation guide of the parameters presented in the Running Performance page

(the guide is also available as a pop-up window in the software application by clicking the “info” button at the upper right corner of the Running Performance page). A more detailed description of the parameters is then given in the subsections that follow.

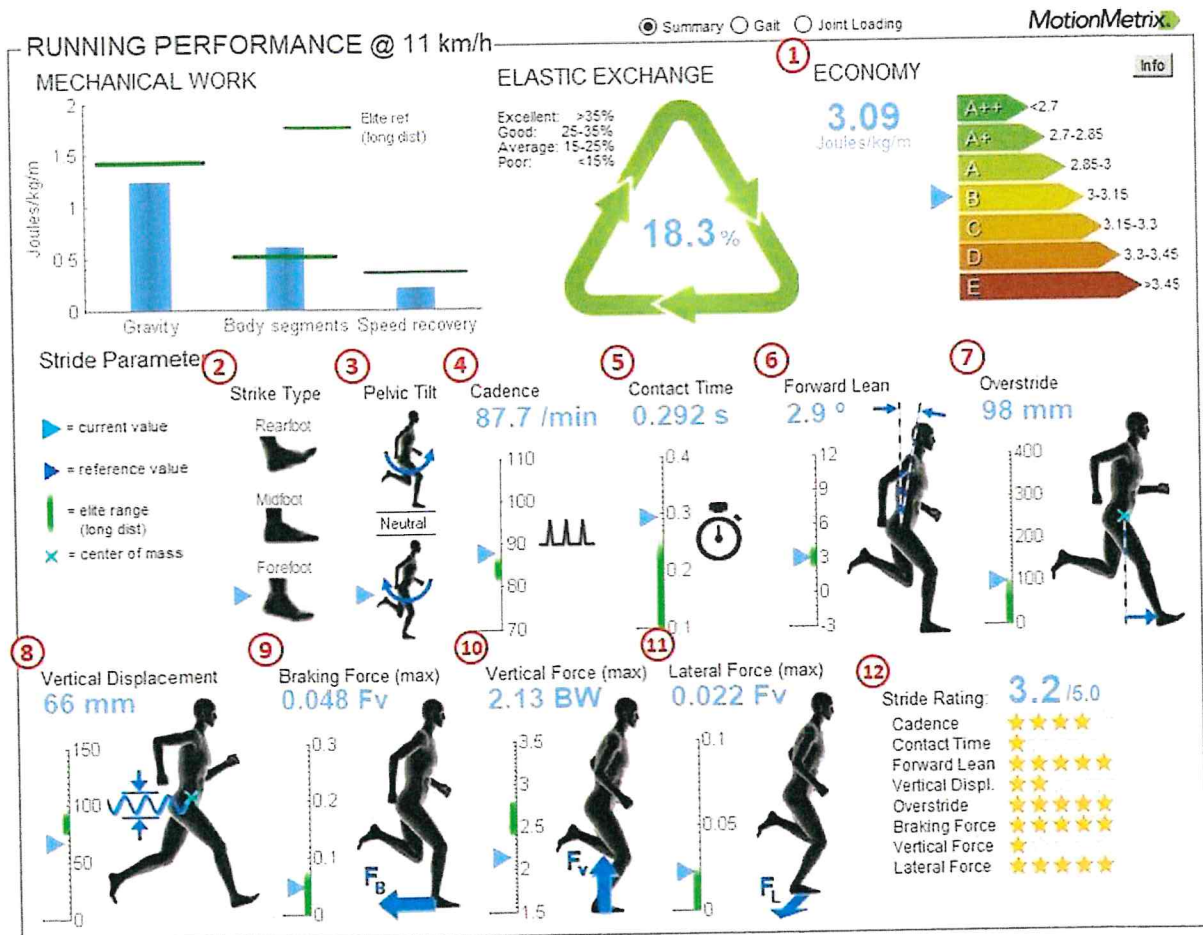


Figure 20. The Running Performance page

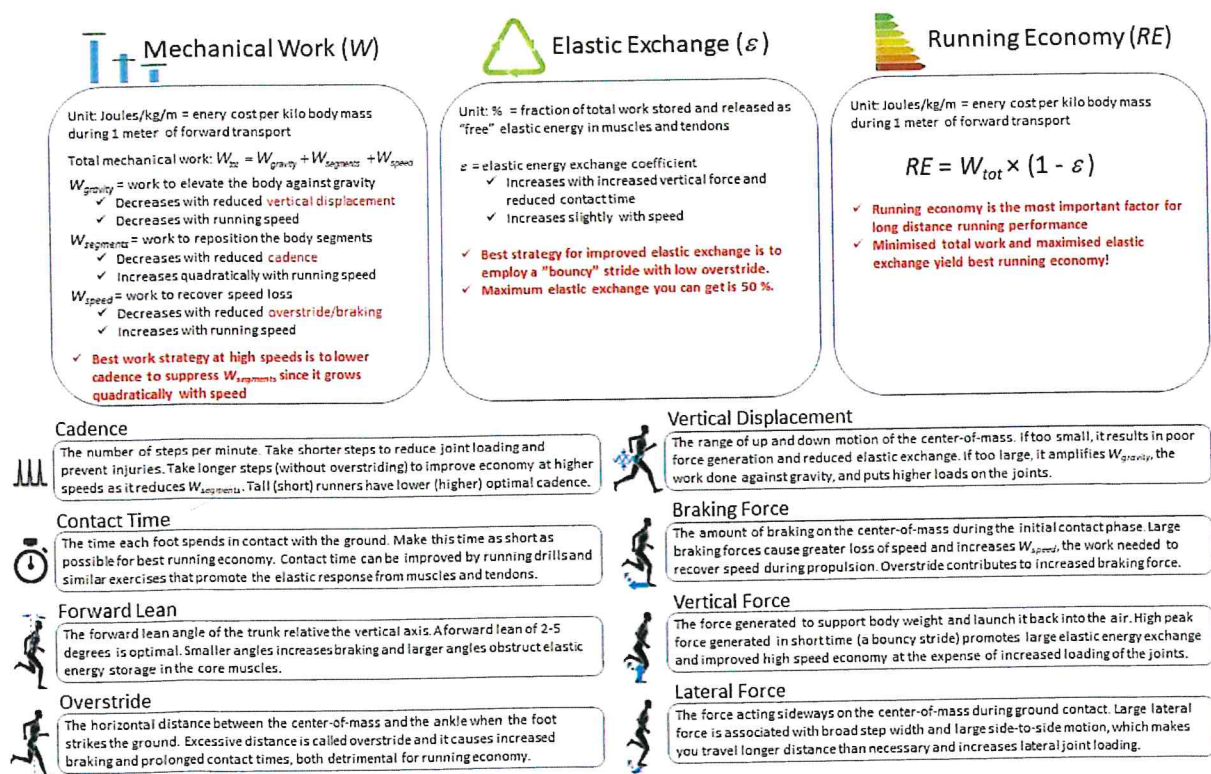


Figure 21. Quick guide to the energies behind MotionMetrix's running economy and associated stride parameters

5.1.1 Running Economy, Work and Elastic Exchange ①

Background to MotionMetrix's Running Economy

Running Economy (RE) is the best predictor for long distance running performance and it is predominantly determined by the efficiency of the runner's mechanical motion. MotionMetrix's RE value originates from the total mechanical work required to maintain forward motion when running at a constant speed: $W_{\text{tot}} = W_{\text{int}} + W_{\text{ext}}$, where W_{int} is the internal mechanical work required to displace the body segments relative the center-of-mass (CoM) and W_{ext} the external mechanical work required to lift the CoM against gravity and to recover speed loss. W_{tot} can be reduced significantly, up to 50 %, by storage and release of elastic energy ("elastic exchange") in tendons and muscles which scales with how quickly the runner is able to generate force.

These are the fundamental mechanical energy processes involved in human running and they are all accounted for in full in MotionMetrix's RE value.

Interpretation of the RE value

The RE value is given in the unit Joules/kg/m and is a measure of how much energy it takes to move one kilo of your body mass one meter forward at the given running speed. The lower the RE value the better. The RE result is ranked with respect to a reference group of 600 runners, beginners to elite, all who have taken the same test. An RE value of 3.08 J/kg/m corresponds to approximately the average value of the reference group (the 50th percentile rank) and places the runner in the center of the "B" class. About 2 % of the runners in the reference group managed to reach the "A++" level which requires RE values < 2.7 J/kg/m.

Since the RE is given per unit distance, one can directly compare RE values at different running speeds. For instance, if you do a lot of distance running at 14 km/h, it is possible that your RE value will be lower here than at 12 km/h simply because the movement pattern is more habituated. Another way to put it is that it costs you less energy to travel a distance of 1 m when running at 14 km/h compared to 12 km/h.

Marathon runners who are adapted to large training volumes at speeds ranging from slow distance up to their marathon race speed are generally more economic in this range compared to, for example, middle distance runners. Not too surprisingly, at higher speeds than their competition speed, many Marathon runners will drop in efficiency while the mid-distance runners can show the opposite trend and become gradually more efficient the higher the speed. In this way, you can obtain your personal running profile with MotionMetrix by testing your RE at different speeds.

Another way of using the RE values is to compare your performance at your most common distance running speed at which you do most of the training compared to your favorite racing speed, for example at 10k. If your RE at your regular distance speed is notably worse than at your racing speed, one can question if all that distance running actually adds so much value to your race performance unless you adjust your running stride to better resemble the one used at race pace.

Correlation with VO_2

Independent validation tests have shown that there exists a significant correlation ($R^2 > 0.6$, see Figure 22) between MotionMetrix's RE value and RE measured by oxygen consumption (VO_2) at submaximal speeds. An important distinction between these methods is that a VO_2 test accounts for all metabolic

processes in the body while MotionMetrix exclusively separates out the mechanical contribution. Running economy measurements by VO_2 are not particularly suited for monitoring instantaneous effects of stride corrections. Even if a correction yields a mechanically more efficient motion, it may initially yield an increase in VO_2 because the muscles are not adapted to the new motion. It could take weeks of habituation before the true effect of the correction is seen in VO_2 . MotionMetrix's mechanical RE is unique in the way that it provides an instant energy response to stride corrections since it ignores all such physiological aspects.

Running Economy: MotionMetrix's RE vs. $\text{VO}_{2\text{submax}}$ (n = 10)

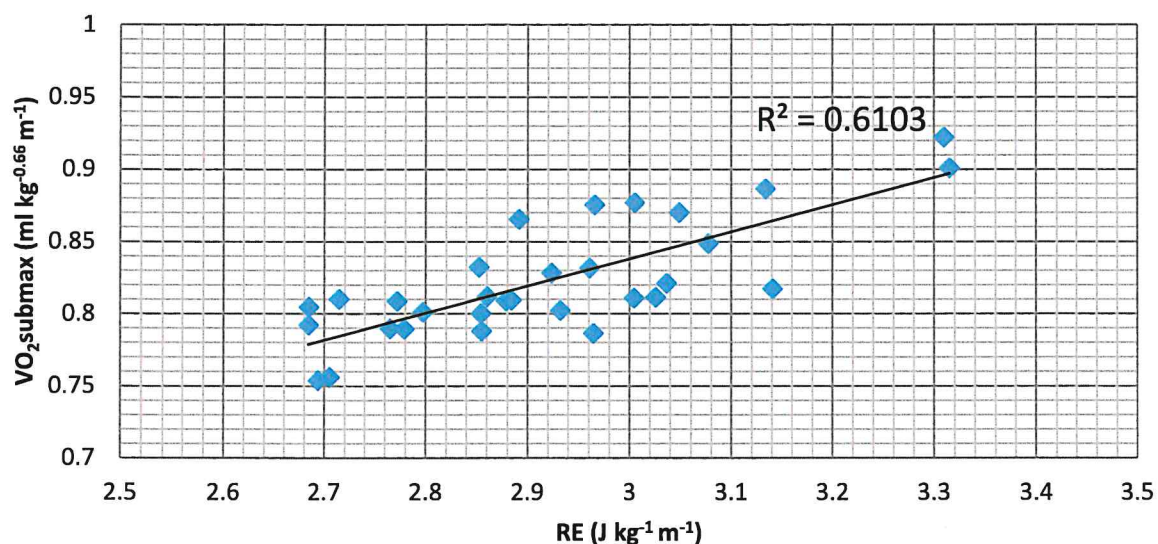


Figure 22. Correlation between MotionMetrix's running economy value and submaximal oxygen consumption

Strategies to improve RE

If only one parameter could be selected to coarsely distinguish efficient running mechanics from insufficient, it should be the horizontal distance between the footstrike position and the center-of-mass (CoM), called "overstride" in the application. In other words, how far in front of the body the foot initially touches the ground. The overstride is an indication (but not a direct measure) of the amount of elastic energy that the runner will be able to accumulate from initial contact to mid-stance where max leg compression occurs. The optimal accumulation of elastic energy is achieved by generating as much force as possible at the shortest possible time and this will automatically be accomplished if the runner manages to bring the footstrike closer to the CoM. Since efficient use of elastic energy can reduce the total energy expenditure by up to 50 %, it is certainly worth the effort.

The rest is a matter of cadence (stride frequency, number of strides per minute). There are basically two fundamental types of economic running styles and we can call them "gliders" and "bouncers" which well describes how we visually perceive these styles. These styles are equivalent to the profiles Quick Stepper (= glider) and Eco Sprinter (= bouncer), in the Runner Profile analysis (see section 5.1.13). The profile Power Racer also belongs to the bouncer category but this profile is more a Gliders are characterized by an elevated cadence (fast short steps), a low vertical displacement but just enough flight time to manage a footstrike position close to the CoM. In contrast, bouncers run with a cadence slightly on the low side, a notable vertical displacement and plenty of flight time to enable a footstrike

position close to the CoM. In terms of mechanical work, gliders spend more work displacing the body segments and less work against gravity (high W_{int} term, low W_{ext} term) and vice versa for the bouncers. Runners may in principle switch between these two economic stride types by simply increasing or decreasing the cadence (due to the inverse relationship between cadence and vertical displacement, see Table 3) as long as the footstrike position is kept close to the CoM for optimal elastic recoil.

So, should one target to run like a glider or a bouncer? It really depends on the speed and distance range you want to perform in and how much load you are prepared to apply on your lower body. Figure 23 and Figure 24 show typical diagrams over how the mechanical work and maximum vertical force, respectively, evolve with running speed for the two running styles. Evidently, if you want to be economic also at higher speeds (approximately $> 15 \text{ km/h}$ or 4 min/km), you need to be a bouncer. In fact, the vast majority of elite long-distance runners, such as the elite reference group in MotionMetrix, are bouncers. Even at marathon distances. Worth noting is that this type of stride is more demanding on the lower body joints due to the higher vertical force and therefore the runner must be able to cope with these loads. For a novice runner who has not developed sufficient strength in muscles, tendons and ligaments to withstand these loads, the glider type of stride can be a preferred start in order to minimize risk of overuse injuries but still enjoy efficient running.

The MotionMetrix stride rating feature (section 5.1.12) is designed for maximized economy towards the higher end of the speed range and the rating scale has been calibrated by the elite reference group. In other words, the rating guides you to run like a bouncer.

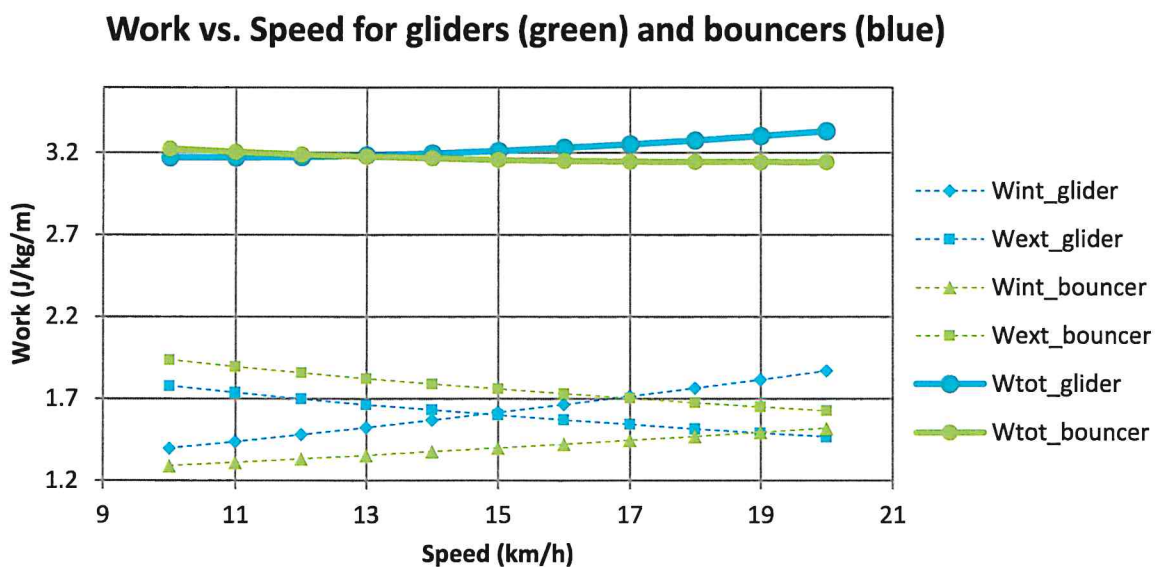


Figure 23. Running speed dependence for the internal (W_{int}), external (W_{ext}) and total (W_{tot}) work for the two different running styles gliders (blue) and bouncers (green).

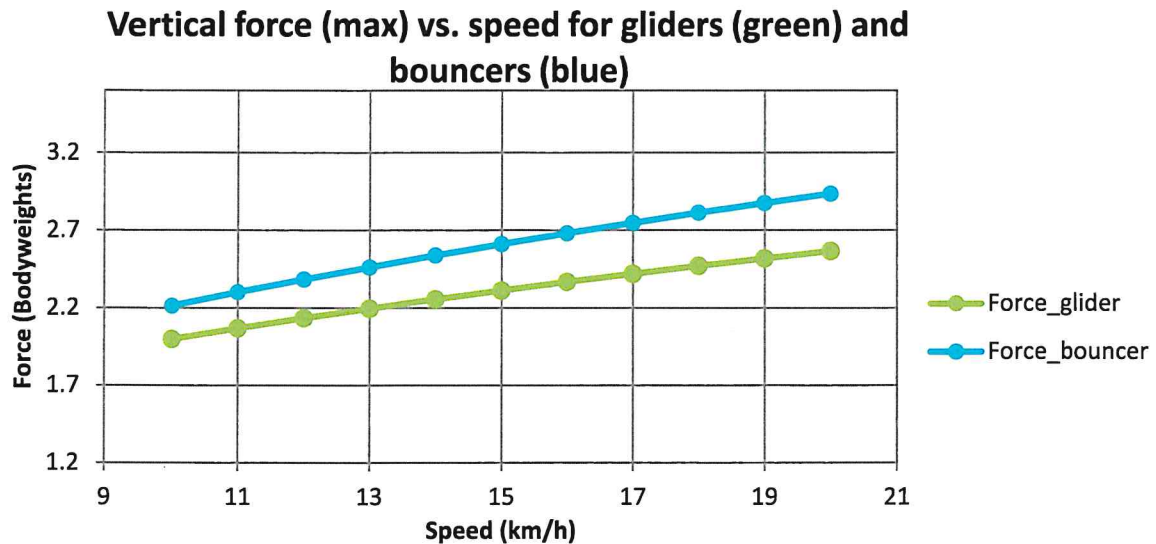


Figure 24. Vertical force (max) as function of running speed for average gliders (green) and bouncers (blue).

Example. A runner obtains 2.83 J/kg/m in RE value when running at 12 km/h and qualifies into "A+" level, which is a very good result. However, the average stride rating is quite poor, only 3.1. How come? This usually happens for runners with excessive stride frequencies at relatively low running speeds. MotionMetrix does not promote this type of stride since at higher speeds, this is no longer as efficient. The intention with the stride rating is to guide the runner towards a stride that is efficient also at the highest speeds. Here, it becomes costly to move the body segments so rapidly and therefore a lower frequency stride is to be preferred as long as the footstrike position is kept close to the center-of-mass. A close footstrike position will promote a high rate of force generation, as evidenced by a reduced contact time and increased vertical force and subsequently an improved elastic exchange and RE.

Example. A runner obtains an RE value of 3.19 J/kg/m is rated as "C" level, which is below average performance. Characteristic for this runner is a low cadence and significant overstride. The former parameter yields an increased vertical displacement with an increased work against gravity as result and the latter induces a prolonged ground contact time which impairs efficient storage of elastic energy and furthermore increases the braking action, all of which contribute to a degraded RE. The runner is instructed to increase the cadence in order to reduce the vertical displacement since these parameters have a strong inverse relationship. To improve the overstride, the runner is asked to reduce the observed posterior pelvic tilt and "stand taller". In addition, the runner is asked to relax the knee joint and allow the elastic bounce to accelerate the foot more upwards after toe-off to present less inertia in the forward swing motion of the same leg. After a few iterations using the RE value as steering parameter, the runner manages to implement the corrections in the proper way and reaches a significant improvement in running economy.

Example. A mid-distance elite runner takes a test at 20 km/h, see Figure 25. He reaches an impressive 48 % in elastic exchange which means that close to half of the total mechanical work is returned as “free” elastic recoil energy. Free in the sense that it does not consume any metabolic energy. Due to this efficient energy return, he gets a reasonably good RE value as well despite that he spends a lot of work against gravity. So why is the stride rating only 3.1? The stride rating favors running economy at controlled joint loading levels and not extreme levels. Elastic exchange approaching 50 % is almost always associated with extreme joint loading levels (not shown here) due to the massive vertical force of 3.12 BW (body weights). Sure enough, mid-distance runners only have to manage these loads for shorter periods during reaches and training and the extreme vertical force is key to top speed performance. For a marathon runner on the other hand, with 100+ km in weekly mileage, such loading levels are likely to cause some damage. This runner would thus get a smoother long-distance ride with improved economy if he increased his cadence a couple of strides/min to reduce the vertical displacement and force.

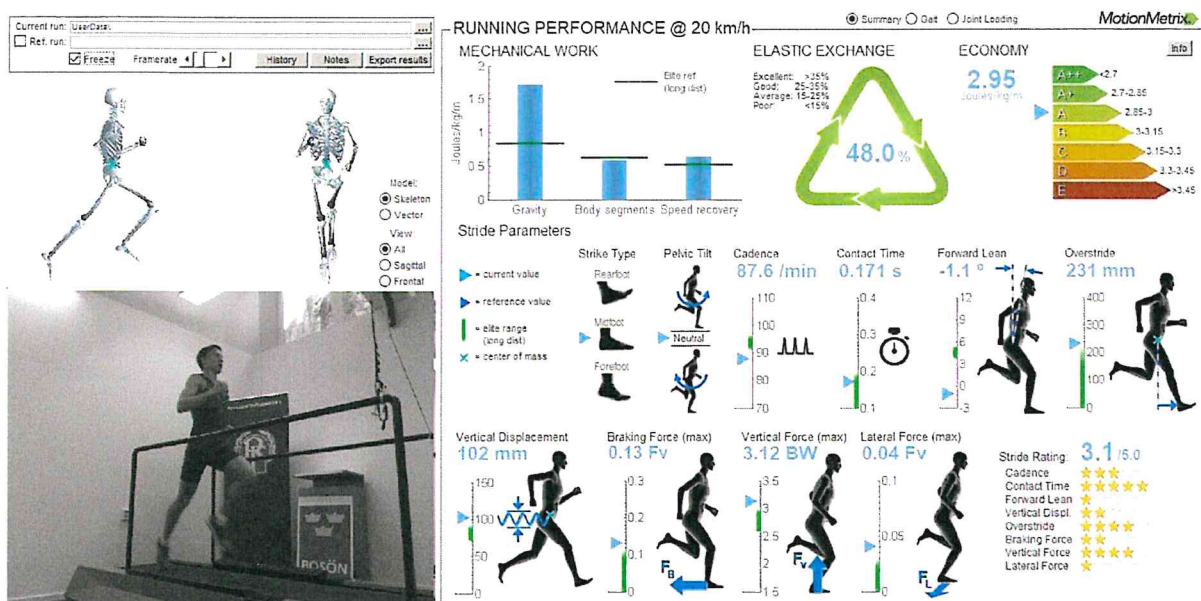


Figure 25. A mid-distance elite runner with very high elastic exchange and reasonably good economy receives poor stride rating because of the excessive vertical displacement and force which results in extreme loads applied on the lower limbs.

5.1.2 Strike Type ②

Indicates if you land on your rear- mid- or forefoot. Strike type is not rated as an impact factor for Running economy.

5.1.3 Pelvic Tilt ③

Indicates if you have a neutral posture, if you tend to sit down or if your body is bent backwards. Pelvic tilt is not rated as impact factor for running economy

5.1.4 Cadence ④

The number of stride cycles per minute. Optimal cadence increases slightly with running speed. For a tall runner, the optimal cadence is a little lower than nominal and the contrary for short runners. Too low cadence often results in excessive overstride (a foot strike position far in front of the center of mass), increased vertical displacement and prolonged ground contact times, all of which contribute negatively to the running economy. Excessive cadence amplifies the internal work (the work done to

move the limbs relative the center of mass) which becomes costly at higher speeds. While a high cadence has the positive effect of reducing contact time, the elastic recoil is impaired due to loss of vertical force and consequently the running economy deteriorates.

5.1.5 Contact Time ⑤

Most of the mechanical work in running is done when the foot is in contact with the ground, to support the body weight and to recover speed lost in the braking phase. Therefore, the contact time is an important factor for running economy. The most economic runners have short contact times since the rate of generating force is known to couple directly to reduced cost of running. Ways to reduce contact time can be to increase cadence (preferably not at the expense of reduced vertical force) or to reduce overstride. Running drills and plyometric training has also shown positive effects on reducing contact times.

5.1.6 Forward Lean ⑥

The angle of the trunk relative the vertical axis in the sagittal plane. A slight forward lean of the upper body is in most cases beneficial to reduce the amount of braking force.

5.1.7 Overstride ⑦

The horizontal (antero-posterior) distance (in mm) between the ankle joint and the ground projection of the center-of-mass at the moment the foot strikes the ground. A footstrike position far in front of the center-of-mass, generally referred to as overstride, leads to reduced force generation rate and degraded running economy.

5.1.8 Vertical Displacement ⑧

The vertical displacement (in mm) is defined as the range of motion of the center of mass along the vertical axis, or basically how much you oscillate up and down while running. An insufficient vertical displacement results in a low trajectory of the center-of-mass and typically a premature touchdown of the swing leg yielding an increased braking action. Also, the vertical force may drop significantly below the optimal level which has a negative impact on running economy (see 5.1.13). Excessive vertical displacements, on the other hand, increases the work done against gravity and subsequently increased energy costs unless the ground contact time can be kept short.

5.1.9 Braking Force (max) ⑨

The maximum (antero-posterior) horizontal force generated between footstrike and mid-stance (referred to as the braking phase). The unit is given in fractions of vertical force max (F_v). Large braking forces cause greater loss of speed that needs to be recovered during propulsion and subsequently costs more energy. Excessive overstride and insufficient forward lean are examples of contributing factors to increased braking force.

5.1.10 Vertical Force (max) ⑩

The maximum vertical force (in unit BW, body weights) exerted on the ground during the stance phase. Maximum vertical force is normally generated at mid-stance, in the transition point between braking and propulsion. Sufficient vertical force is needed to stretch the elastic elements in the leg in order to make optimal use of the recoil energy. Too little force reduces the degree of energy recycling through elastic recoil. Excessive vertical force, when associated with a large leg compression (high knee flex angles), increases the work against gravity and thus an increased energy cost.

5.1.11 Lateral Force (max) ⑪

The maximum horizontal (medio-lateral or sideways) force generated during stance. The unit is given in fraction of vertical force max (F_v). Lateral force is a measure of the amount of side to side motion of the center of mass and most of that motion is wasted energy. Runners that generate large lateral forces usually exhibit a broad step separation (more about that in the Gait section next).

5.1.12 Stride Rating ⑫

The selected running stride parameters have all shown to have impact on the running economy, both in scientific literature and from MotionMetrix tests, some more and some less. Each parameter is rated with one to five stars where five stars correspond to long distance elite level performance. The elite level is based on measured stride data from a group of (male) long distance elite runners. Also presented is an average rating value which is calculated as the weighed mean of all the parameter ratings. Each parameter is assigned a weight 1 (low) to 3 (high) mainly depending on its running economy impact but also to a certain extent its impact on elastic exchange and joint loading. The weights are distributed as follows:

Table 2. Stride parameter impact on running economy, 1 = low, 2 = medium and 3 = high.

Parameter	Weight
Cadence	2
Contact Time	3
Forward Lean	1
Vertical Displacement	2
Overstride	3
Braking Force	2
Vertical Force	3
Lateral Force	2

High impact parameters on running economy are contact time, vertical force and overstride which all contribute to the rate of generating force, an important factor for improved running economy. In order not to encourage extreme joint loading levels, the max vertical force rating has an upper limit above which the rating starts to degrade.

Worth mentioning is that there are two categories of runners that may score great in running economy but still obtain only a moderate stride rating score, those are gliders (described in 5.1.1) and mid-distance runners (Figure 25). Gliders are down rated because of their insufficient elastic exchange (poor economy forecast at high speeds) that results from the low vertical peak forces typical for this type of stride. Mid-distance runner, on the other hand, have exceptionally high elastic exchange but get down rated because of the extreme joint loading levels on the lower limbs resulting from the excessive vertical forces. For long distance running, such extreme loading levels should be avoided in order to reduce the risk of overuse injuries.

This section is concluded by the two tables below that show how the eight rated stride parameters correlate with other stride parameters (Table 3) and their quantitative impact on running economy, elastic exchange and joint loading (Table 4).

Table 3. Stride parameter correlations

An increase in	Correlates strongly with	Correlates moderately with
Cadence	<ul style="list-style-type: none"> • Decreased vertical displacement • Decreased external work • Increased internal work • Decreased sagittal knee moment • Decreased vertical force 	<ul style="list-style-type: none"> • Decreased contact time • Decreased max knee flex @ stance • Decreased max knee flex @ swing • Decreased frontal hip adduction moment
Contact Time	<ul style="list-style-type: none"> • Decreased vertical force rate • Decreased vertical force 	<ul style="list-style-type: none"> • Increased leg compression during stance • Increased knee varus alignment • Decreased max knee flex @ swing • Increased max knee flex @ stance
Forward Lean	n.a.	<ul style="list-style-type: none"> • Decreased sagittal hip moment
Vertical Displacement	<ul style="list-style-type: none"> • Increased external work • Increased vertical force • Decreased internal work • Increased vertical force rate • Increased sagittal knee moment • Increased max knee flex @ swing 	<ul style="list-style-type: none"> • Increased frontal hip adduction moment
Overstride	<ul style="list-style-type: none"> • Increased shank angle @ landing • Decreased vertical force rate • Decreased vertical force • Decreased knee flex @ landing • Increased braking force • Increased contact time 	
Braking Force	<ul style="list-style-type: none"> • Increased overstride • Heelstrike • Increased shank angle @ landing 	
Vertical Force	<ul style="list-style-type: none"> • Increased vertical force rate • Increased knee flex @ swing • Decreased shank angle @ landing 	<ul style="list-style-type: none"> • Increased knee flex @ landing • Increased sagittal knee moment • Increased frontal hip adduction moment
Lateral Force	<ul style="list-style-type: none"> • Increased step separation • Increased knee medial force • Increased hip medial force 	<ul style="list-style-type: none"> • Increased contact time • Decreased vertical force rate

Table 4. Stride parameter correlation with running economy, elastic exchange and joint loading expressed in R^2 correlation coefficients, where $R^2 = \pm 1$ is absolute positive/negative correlation and $R^2 = 0$ is no correlation.

	Running economy	Elastic exchange	Joint Loading
Cadence	0.04	-0.31	-0.48
Contact Time	0.81	-0.70	-0.09
Forward Lean	0.10	-0.07	-0.03
Vertical Displacement	-0.32	0.60	0.64
Overstride	0.49	-0.49	-0.24
Braking Force	0.24	-0.27	-0.04
Vertical Force	-0.67	0.80	0.62
Lateral Force	0.27	-0.24	0.25

5.1.13 Runner Profile (introduced in R6.0)

The runner profiles have been derived from a large data set ($N > 1000$ runners) using cluster analysis. The model converged to six fundamental profiles, all with their unique set of stride parameters. The runners in the data set were also inquired about race performance, injury incidence, training volume, shoe preference etc. This allows us to say something about performance and injuries of each profile and subsequently give generic advice how to improve. This the job of our “e-coach”. The Runner Profile analysis is located on the lower half of the Running Performance page and the user can select to show the Runner Profile or the Stride Parameters on this page. A quick reference guide can be accessed by pressing the “Info” button, see Figure 26.

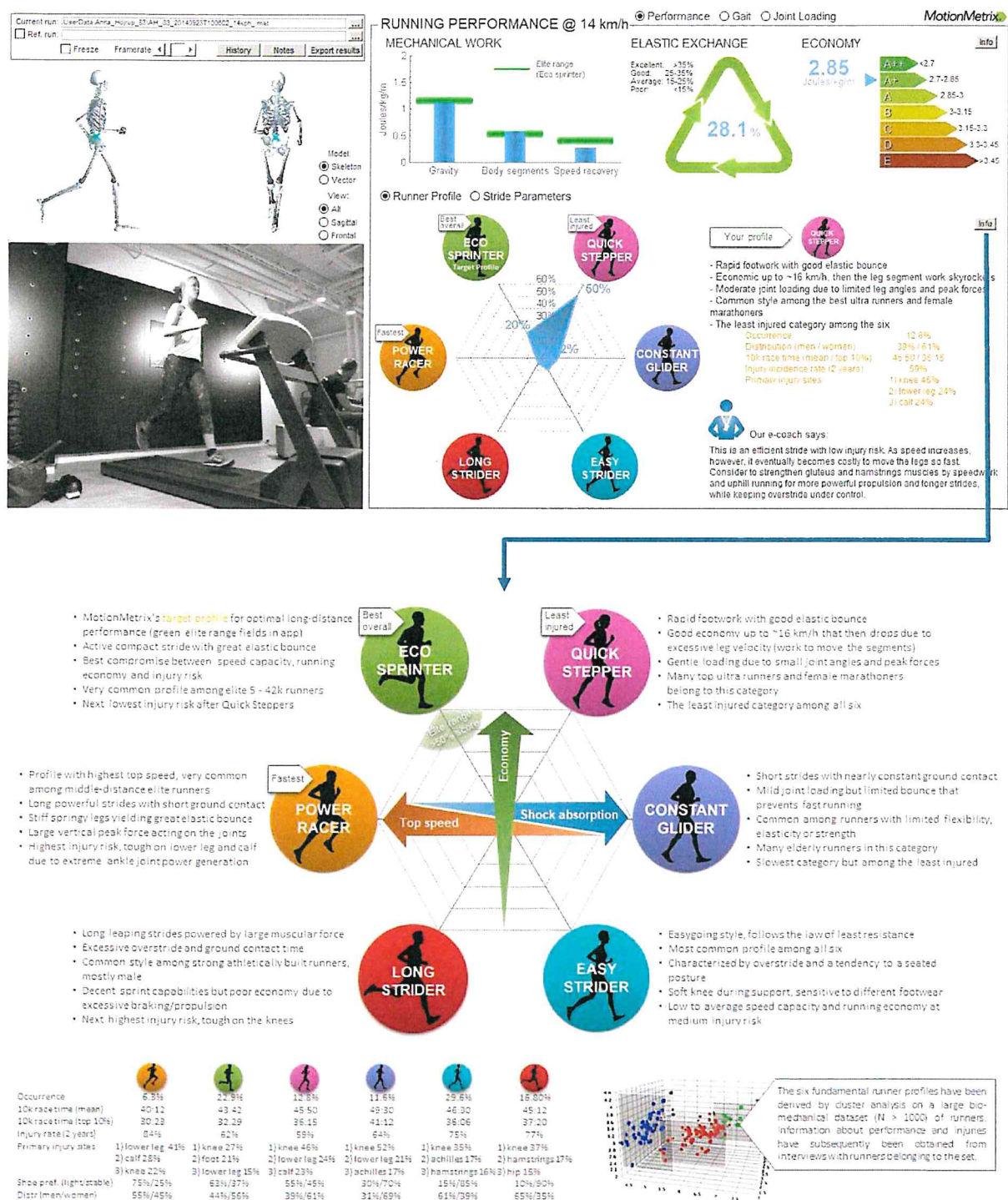


Figure 26. Runner Profile analysis

5.2 Gait Characteristics page

In order to make a complete functional assessment of the runner's biomechanics and to assess injury risk, it is essential to go through the Gait and the Joint Loading pages as well. The Gait Characteristics page details the runner's lower body kinematics in the sagittal and frontal planes. Any asymmetries and anomalies found here are crucial inputs to the overall performance and injury risk assessment of the runner.

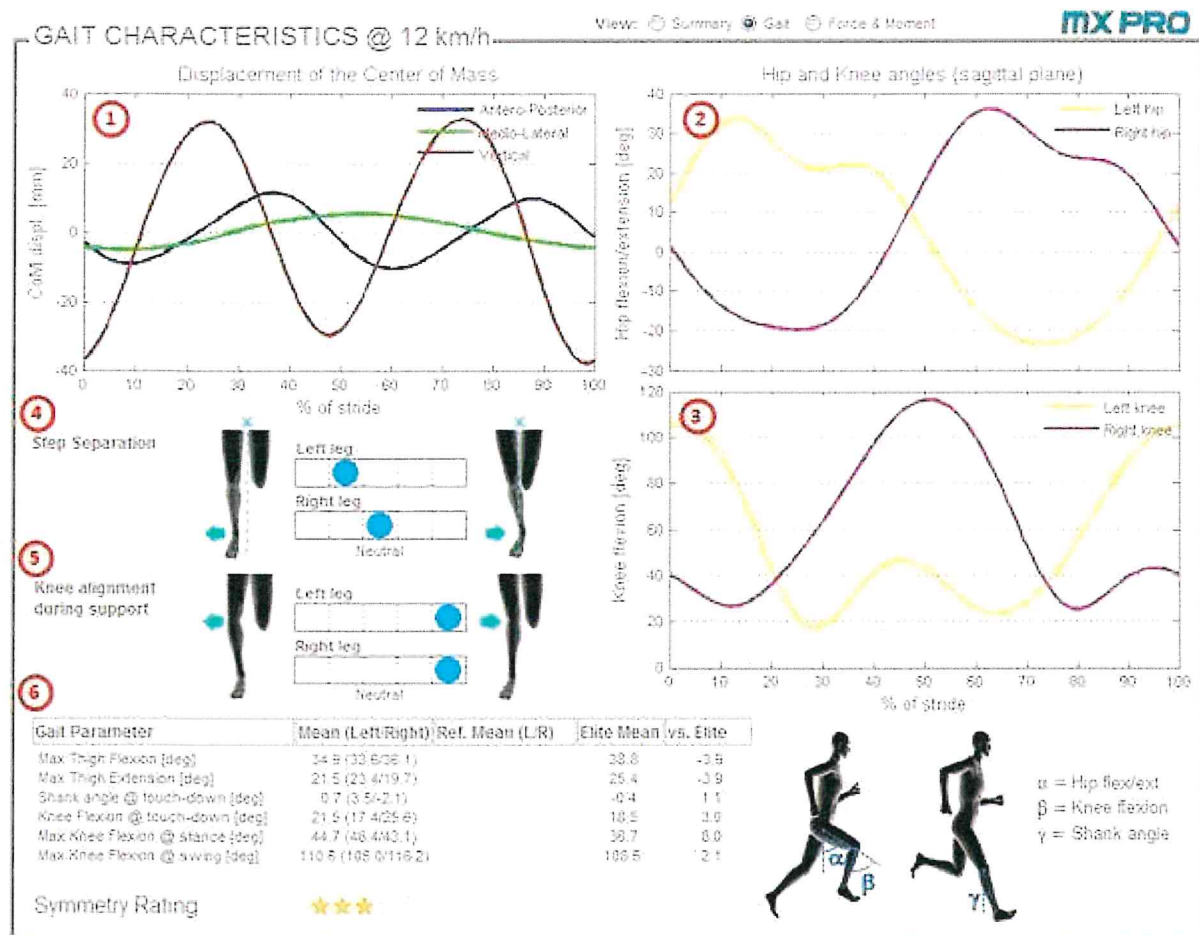


Figure 27. The Gait characteristics page

5.2.1 Displacement of the Center of Mass

Graph displaying the CoM displacement of the whole body in the antero-posterior (blue), medio-lateral (green) and vertical direction (red). The CoM is calculated as the sum of all local CoMs of the individual body segments.

5.2.2 Hip flexion/extension

Graph displaying the hip flexion (positive values) and extension (negative values) angle in the sagittal plane for the left (yellow curve) and right (purple curve) leg, respectively. The hip flexion/extension angle is defined relative to the gravitational axis (angle α in the lower right corner of the above figure).

5.2.3 Knee flexion

Graph displaying the knee flexion angle in the sagittal plane for the left (yellow curve) and right (purple curve) leg, respectively. The knee flexion angle is defined as the angle between the longitudinal axes of the thigh and lower leg (angle β in the lower right corner of the above figure).

5.2.4 Step Separation

Defined as the maximum separation distance between the left and right ankle during stance. The step separation range is calibrated against the results from 600 mixed-level runners at 12 km/h. At higher speeds, the step separation shrinks due to the increased pelvic rotation. The step separation can be neutral (centered blue bullet), wide (blue bullet displaced to the left) or narrow (blue bullet displaced to the right). Step separation largely impacts the magnitude of the frontal plane moments on the lower

limb joints. A wide step separation generally reduces the frontal plane moments but increases the medio-lateral joint forces, while a narrow step separation leads to increased frontal moments.

5.2.5 Knee alignment during support

Defined as the frontal plane knee angle at mid-support. The range of motion is compared with the results from 600 all-level runners. The knee alignment can be neutral (centered blue bullet), varus/bowlegged (blue bullet to the left) or valgus/knocked-knees (blue bullet to the right). The knee alignment range is calibrated against the results from 600 mixed-level runners at 12 km/h. Exaggerated varus alignment yield coupes to increased frontal knee moments, which in turn can results in various types of knee problems.

5.2.6 Gait parameters table

The table shows selected critical angles of the lower limbs (mean and corresponding left and right values within parenthesis). Also shown in the table are the "Elite Mean" values and the "vs. Elite" values, the latter which represents the difference between the current mean and elite mean values. Below the table is a rating of bilateral gait symmetry of the runner, which takes into account all the left - right differences. The smaller differences, the better the rating.

5.3 Joint Loading page

Running is a weight bearing exercise that puts a lot of demand on the lower limbs. During the support phase, ground reaction forces of over 3 times the bodyweight can be generated. Over 50% of all recreational runners will sustain a running-related injury each year. About half of those injuries occur at the knee. While there may be many contributing factors to the development of an injury, it is ultimately the load applied to the lower limb joints and the runner's ability to withstand that load that will decide the outcome.

MotionMetrix's joint loading analysis is based on inverse dynamics calculations which yield the external forces and moments acting on a joint. The major advantage with this type of analysis is perhaps best described by citing one of the leading textbooks in biomechanics *Biomechanics and motor control in human movement* by David A. Winter: "The inverse solution is a very powerful tool in gaining insight into the net summation of all muscle activity at each joint. Such information is very useful to the coach, surgeon, therapist and kinesiologist in their diagnostic assessments. The effects of training, therapy or surgery is extremely evident at this level of assessment, while they often remain unseen in the original motion pattern."

Special focus has been put on the maximum loading on the knee and hip joints during the support. Maximum loading of a joint usually occurs at around mid-support when the vertical ground reaction force reaches its maximum value. To rate the level of joint loading, an index 0-100 has been introduced where 0 is minimum loading and 100 is maximum. The index scale has been calibrated by the result from a group of 600 mixed-level runners running at 9-15 km/h. Runners with a loading index of 50 and above may be considered to be exposed to an increased risk of sustaining an injury as a result of the comparatively high joint forces and moments. In general, joint loading grows with speed at about the same rate as the vertical ground reaction force grows, about 1-2 % per km/h.

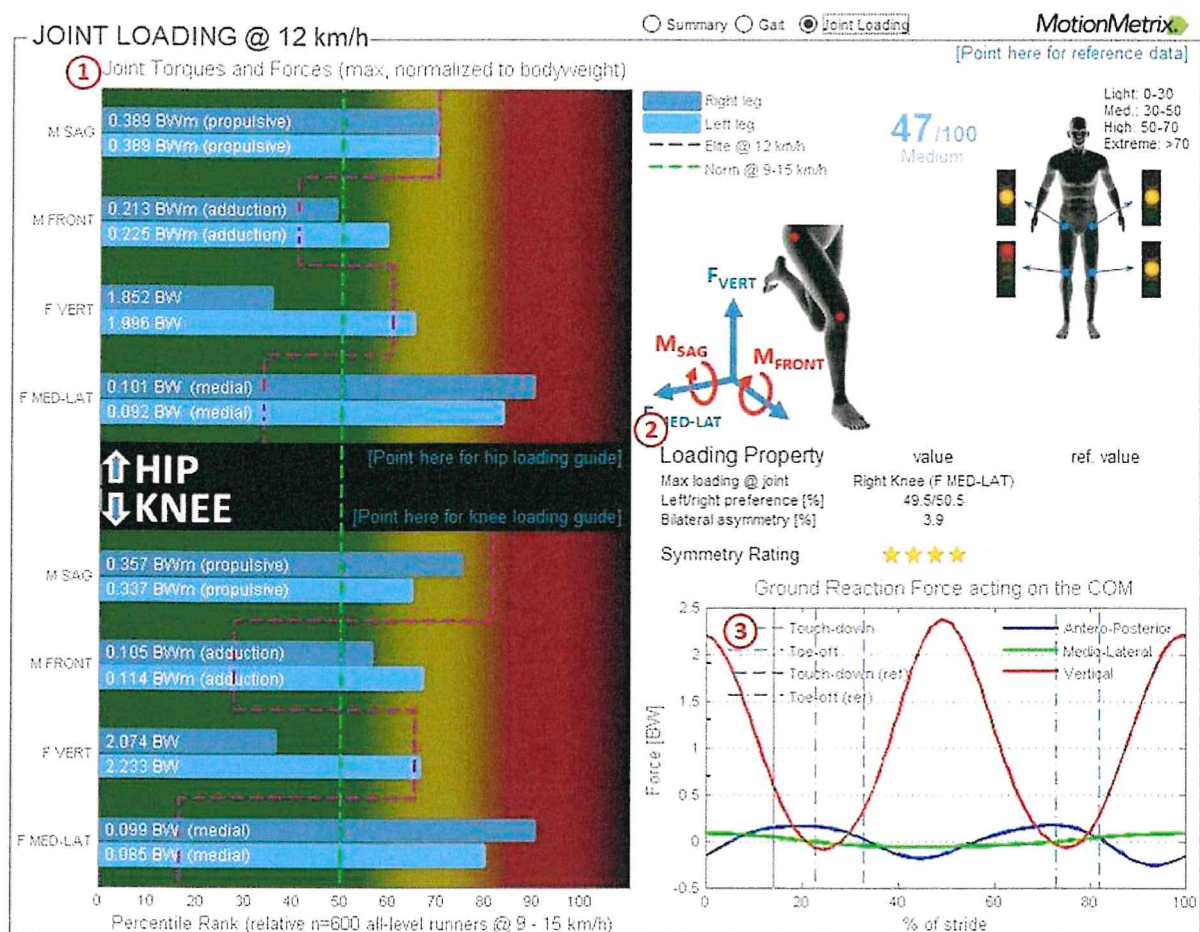


Figure 28. The Joint Loading page

It should be noted that the joint loading is normalized to bodyweight, that is, how much load per kg body mass that is generated in each joint. As an example, if an overweight runner obtains a loading index of 20 one can conclude that his or her running mechanics is advantageous compared to the average runner in terms of reduced joint loading. However, accounting for the runner's body mass, the risk of injury may still be significant due to that the effective load becomes high.

The traffic light rating is an aid to quickly screen any loading hotspots and, hence, areas with increased injury risk exposure. Green represents a loading level below or at normal level, yellow is above the normal (60 - 80th percentile) and red is significantly above the normal (> 80th percentile). The rating is always in relation to the reference group of 600 mixed-level runners at 9-15 km/h.

Paradoxically, joint loading shows an inverse relationship to Running economy for most runners (RE improves with increased joint loading). Improvements in Running economy often involves reduced ground contact times. However, shorter ground contact times yield higher vertical peak forces which in turn contributes to increase the overall joint loading. Therefore, it is important to monitor how the joint loading evolves when correcting running strides for improved Running economy. This is especially the case for novice runners who are not trained to handle very large loads. For novice and recreational runners, the most suitable strategy is to target a sound balance between running economy and joint loading.

In running, the joint loading is largely determined by the ground reaction force (GRF) and the alignment (angles) of the lower limb segments during support. To manage the shock produced by the GRF when the foot hits the ground, a complex pattern of joint motions occurs to attenuate the shock and to distribute the load evenly between the ankle, knee and hip joints. Obviously, the motion at a joint can be insufficient, exaggerated or inappropriate in some way which may cause damage to the surrounding structures. As a rule of thumb, insufficient joint motion will result in high reaction forces at the joint whereas excessive joint motion yields high joint moments.

In most cases, it is not intuitive to anticipate joint loading by just looking at the motion pattern since, among other things, the loading at one joint depends on the loading at neighboring joints. However, there are some clean cases that can be studied to help the conceptual understanding and one such example is shown in Figure .

The left skeletal model in Figure 29 has a normal alignment of the knee in the frontal plane while the other one has an excessive varus alignment. At mid-support, the frontal moment of the knee is mainly determined by the product between the GRF and the moment arm d , that is, $M_{\text{FRONT}} = \text{GRF} \times d$. If the GRF is similar between the two cases, the skeletal model with the varus alignment will be subjected to a much higher frontal moment at the knee due to the extended moment arm $d_2 > d_1$. Research has shown that many types of knee pains and injuries, such as knee osteoarthritis, can be associated with high frontal moments.

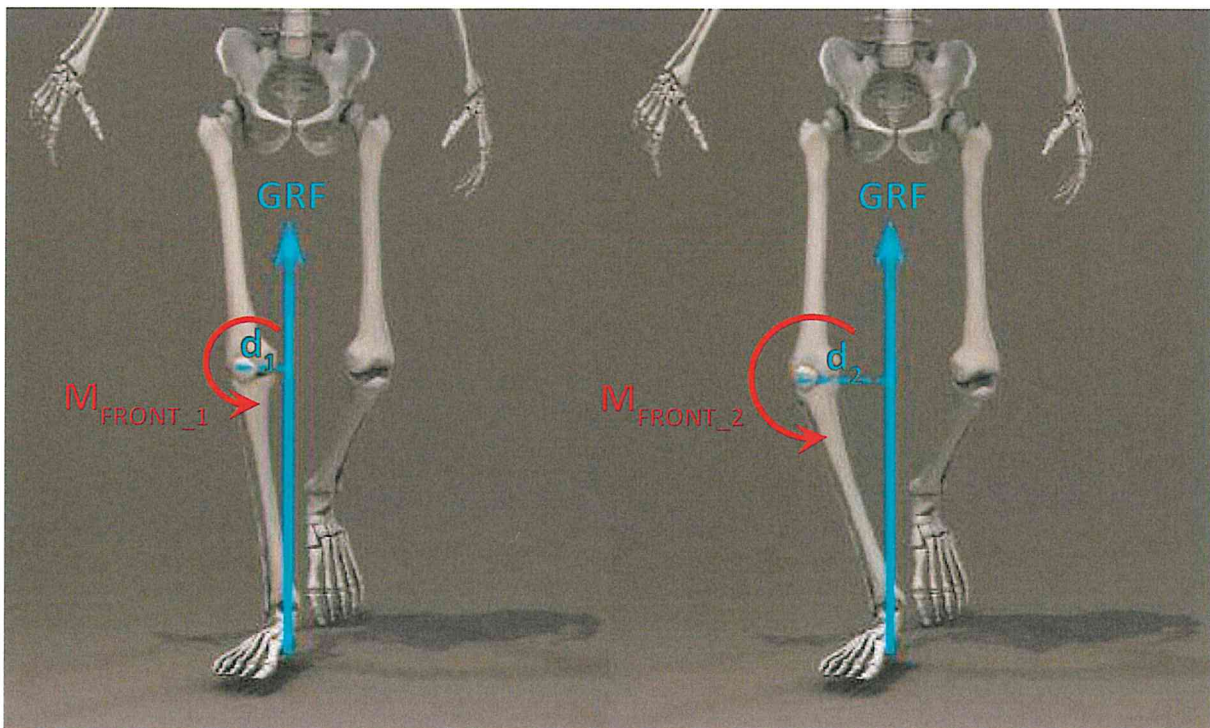


Figure 29. An illustration of how a greater varus alignment of the knee (right image) causes an increased frontal moment due the extended moment arm d_2 .

An efficient but blunt way to reduce the overall joint loading is by reducing the ground reaction force. Practically, this is done easiest by increasing the cadence. However, in many cases, this means a less elastic stride and subsequently a degraded running economy. Better strategies involve looking at specific joint loading variables that stick out and assess how they couple to the runner's motion pattern. If anomalies in the motion pattern can be confirmed, they should, if possible, be corrected

while trying to maintain an efficient stride. More about the correlation between joint loading and running gait in the next section.

5.3.1 Joint torques and forces chart ①

The bar chart in the Joint Loading page (see label 1 in

Figure 28) shows selected peak forces and moments on the hip (upper half of chart) and knee (lower half of chart). Forces are analyzed in two directions, vertical to the joint and lateral (sideways) to the joint and joint moments are analyzed in the sagittal and frontal plane, respectively. The vector diagram to the left of the chart illustrates the orientation of the mentioned forces and moments relative to the runner. All forces and moment are normalized to body mass. This means that two runners with identical running gait but different body mass but will get the exactly the same joint loading results in the chart. In the overall injury risk assessment however, the body mass should be accounted for which means that the heavier runner is exposed to an augmented risk.

The length of each bar in the chart indicates how a specific force or moment scales in relation to the normal distribution for a reference group of 600 all-level runners running at 9-15 km/h. Special attention should be put on bars extending into the red area, which corresponds to joint loads above the 80th percentile of the reference group. The bars are also labeled with their actual values and units. The force unit is bodyweights (BW) and the moment unit is bodyweights x meters (BWm).

Reference group data and elite level data are available in a pop-up table for comparison by moving the mouse pointer to the text field [Point here for reference data] at the upper right corner of the chart.

Every runner has his or her unique running gait and subsequently a unique distribution of joint loads. Nevertheless, there are some basic relationships that are true for most runners. As was mentioned before, it is not always straightforward to explain how an increase in a joint loading parameter is related to the motion pattern. To facilitate this, MotionMetrix has derived these relationships by correlation analysis using its large database of runners and the results are presented in Table 5. Only variables with correlation coefficient 0.3 or higher has been included in the table. The correlation data from Table 5 is available also in the software application in the form of pop-up tables, one for the hip and the other for the knee. The tables are displayed by moving the mouse pointer to the fields “[Move here for hip loading guide]” or “[Move here for knee loading guide]”.

Table 5. Joint loading variables and correlated stride parameters.

An increase in	Correlates strongly with	Correlates moderately with
Sagittal hip moment M_{SAG}	<ul style="list-style-type: none"> Increased hip extension 	<ul style="list-style-type: none"> Decreased overstride Decreased forward lean
Frontal hip moment M_{FRONT}	<ul style="list-style-type: none"> Decreased step separation Increased vertical displacement Increased max vertical force 	<ul style="list-style-type: none"> Decreased cadence Decreased max knee flexion @ stance Decreased knee flexion @ landing
Vertical hip force F_{VERT}	<ul style="list-style-type: none"> Increased vertical force Increased vertical displacement Increased max knee flex @ swing Decreased cadence 	
Medio-lateral hip force $F_{MED-LAT}$	<ul style="list-style-type: none"> Increased lateral force Increased step width 	<ul style="list-style-type: none"> Increased body length
Sagittal knee moment M_{SAG}	<ul style="list-style-type: none"> Decreased shank angle @ landing Increased knee flexion @ landing Increased max knee flex @ stance Increased vertical force Increased vertical displacement Decreased cadence 	<ul style="list-style-type: none"> Decreased overstride
Frontal knee moment M_{FRONT}	<ul style="list-style-type: none"> Decreased step separation Increased knee varus alignment (bowlegs) 	<ul style="list-style-type: none"> Decreased cadence
Vertical knee force F_{VERT}	<ul style="list-style-type: none"> Increased vertical force Increased vertical displacement Increased max knee flex @ swing Decreased cadence 	
Medio-lateral knee force $F_{MED-LAT}$	<ul style="list-style-type: none"> Increased lateral force Increased shank angle Decreased knee angle @ landing Decreased max knee angle @ stance 	<ul style="list-style-type: none"> Increased step with



Example: A runner complains about recurring knee pain on the left side and takes a MotionMetrix test at a physiotherapy clinic. The runner has always used shoes with pronation control as a result of a pronation analysis done at the retail store many years ago. The joint loading analysis chart indicates a frontal moment on the left knee above the 80th percentile which places the runner in the red area of the chart. Loading levels in the red area can be associated with a significantly increased risk of sustaining overuse injuries. The therapist uses the correlation guide in the program and finds that an increased frontal knee moment correlates to a varus type of knee alignment. The therapist switches to the Gait analysis page and finds evidence that the runner indeed has an excessive varus tendency during the left support phase. The runner is recommended to try a neutral shoe in order to reduce the varus alignment. A new test is done with neutral shoes and the varus angle decreases by 0.5 degrees which yields a frontal knee moment below the 60th percentile. Subsequently, the runner has reduced the loading of the knee from an alarming level to a normal level with a good chance of becoming symptom free. The example illustrates the insufficiency of pronation analysis and the importance of assessing the loads above the ankle joint.

Example: A runner scores high in medio-lateral hip force and also reports occasional pains on the side of the hip. The therapist notices in the Gait characteristics panel that the runner has step width above normal. In addition, a forward lean of 1.5 degrees above the optimal angle is observed. The test leader asks the runner to overcompensate the forward lean by a reducing it 2-3 degrees. As a result, the step width becomes normal as well as the medio-lateral hip force. After three months of practice with the reduced forward lean, the runner is free from hip pains. Another positive aspect is that the running economy is improved as well since, with the narrower step width, less kinetic energy is spent side-to-side (smaller moment on the CoM, see Figure 30 below). The effect of narrowing step-width on running economy has been reported in literature as well.

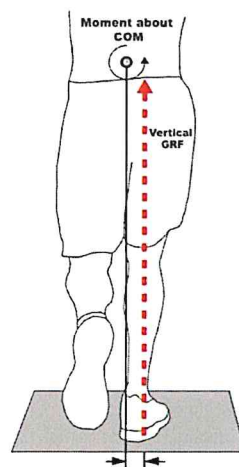


Figure 30. How an increased step width induces an increased moment on the CoM and thus forcing the body to move sideways.

Example: A runner scores red on most of the joint loading parameters in the red, even at the relatively low speed of 12 km/h and complains about frequent periods of involuntary absence from running due to various types of running related injuries. As soon as it is possible to run again, the next problem strikes. The test leader concludes that the underlying cause for the extreme joint loading is the high peak vertical force of 2.87 BW (bodyweights). In these kinds of situations, the best strategy in order to reduce the overall joint loading is to increase the cadence as it efficiently decreases the vertical displacement and consequently the vertical force. Usually, if the peak vertical force is > 2.5 BW, this can be done with maintained running economy.

5.3.2 Joint loading properties table ②

This table shows at which joint the maximum loading occurs and also the type of loading, if the runner prefers to load one leg before and the amount of loading asymmetry between left and right (bilateral). The bilateral symmetry is also rated with stars where five stars is optimum symmetry.

5.3.3 Ground reaction force graph ③

This graph shows the vertical and horizontal components of the ground reaction force (GRF) acting on the center of mass (CoM). The moving cursor indicates at which stage in the stride the runner is at and is synchronized with the animated segment model as well as the video data. Most joint moments and forces will reach their maximum values near the peak vertical GRF. Therefore, it can be of interest to freeze the cursor (by pressing the Freeze button in the control panel) at the peak value and study the posture of the segment model when trying to get a deeper understanding of the mechanisms behind a particular joint loading distribution.

6 Results overview – Clinical Gait

Clinical Gait analysis refers to the systematic study of human walking to distinguish normal function from pathologic condition. MotionMetrix's Clinical Gait module provides a standard set of gait parameters in which most pathologic conditions are reflected. Clinicians can therefore use it to efficiently screen for a variety of conditions and to follow up on corrective measures. Moreover, the Clinical Gait module has many more features that take advantage of the full 3D capabilities which allow for gait assessments previously only possible in advanced medical laboratories.

6.1 Gait Cycle phases and parameters



Figure 31. The reporting format for the gait analysis protocol. Gray fields are normative data (± 1 SD).

The reporting format of the gait analysis protocol is shown in Figure 31. A description of the gait cycle and its phases is beyond scope of this manual and we refer to literature. A comprehensive summary by Dr Jacquelin Perry can be found publicly online here: <http://www.oandplibrary.org/alp/chap13-01.asp> or more in detail in her standard work "Gait Analysis: Normal and Pathological Function" (ISBN 9781556427664).

6.2 Center-of-Mass & Lower Extremities

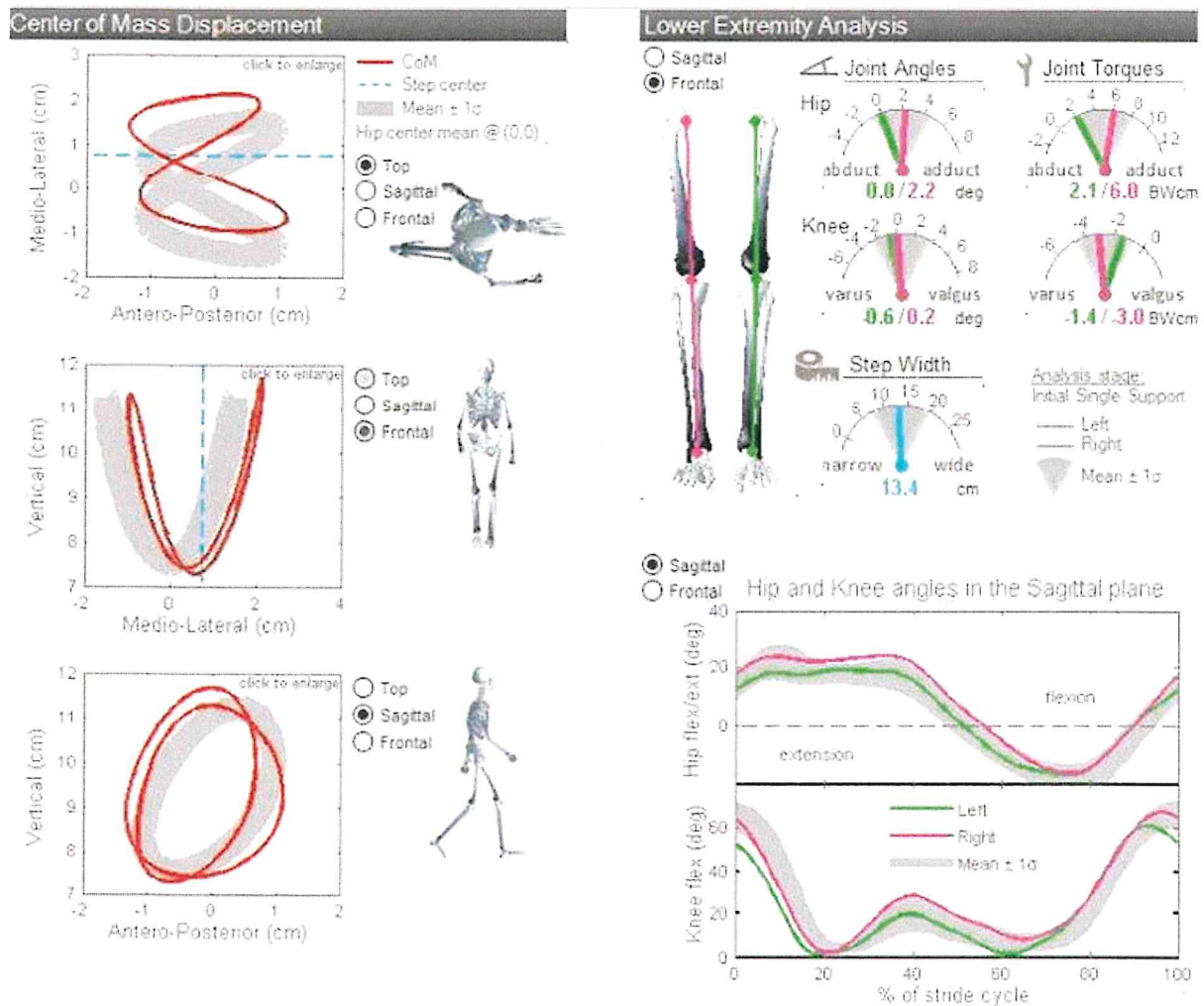


Figure 32. Center-of-Mass displacement in all three anatomic planes and Lower Limbs analysis in frontal and sagittal planes. Gray fields are normative data (± 1 SD).

6.2.1 Center-of-Mass Displacement

The center-of-mass (CoM) is calculated from all the body segments in 3D and its displacement is shown in all anatomical planes. Bilateral asymmetry of the CoM displacement is often indicative of gait impairments.

6.2.2 Lower Extremity Analysis

Here we present hip and knee joint angles in the sagittal and frontal planes. In the frontal plane, the torque (or moment of force) on the hip and knee joints is also given. The torque is derived from inverse dynamics calculations, exactly the same way as in the Running module (see 5.3).

6.3 Stride Variability

Stride or Gait Variability refers to the change in one (or several) gait parameters from one stride to the next. Stride variability has proven to a very useful quantity in the study of, for instance, neurodegenerative diseases, falls risks among elderly and general mobility impairments. We present two types of variabilities, one spatial and one temporal. The spatial variability is the standard deviation of the step width data from the full 30 s recording whereas the temporal variability is the standard

deviation of the gait cycle time data. So, any inconsistencies in step position and timing will show up in these parameters.

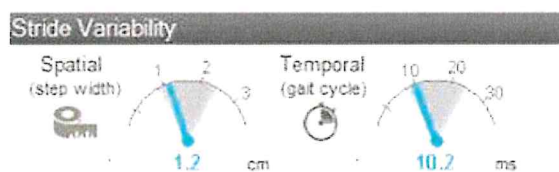


Figure 33. Stride to stride variability in step with and gait cycle time. Gray fields are normative data (± 1 SD).