THE BIOMECHANICS OF WALKING AND RUNNING

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With the increased awareness of the importance of physical activity to general health, walking, jogging, and running have become more popular. Along with this popularity is an increased incidence of chronic walking and running injuries. Although the causes of chronic injuries are varied, a fundamental understanding of the biomechanics of normal walking and running is important before addressing walking and running disorders.

This article discusses different aspects of the biomechanics of gait such as the gait cycle events, joint kinematics (angular changes), and joint kinetics (moments and powers) and compares these aspects as they relate to walking and running. The information presented here is based primarily on electromyo- graphic, joint kinematic, and joint kinetics data obtained using modern computerized gait analysis techniques. With this information the reader will develop an appreciation of the biomechanics of walking and running (Tables 1 and 2) including those increased loads sustained during running (as compared with walking) that form the basis of some chronic running injuries commonly experienced.

Data was collected on normal children during walking and running at the Newington Children's Hospital Gait Analysis Laboratory. More detailed accounts of the methodology have been previously published. In brief, joint kinematic information was obtained by aligning reflective markers to specific bony landmarks on the pelvis, thigh, shank, and foot. The three-dimensional marker trajectories were obtained using multiple infrared cameras (Cohu, San Diego, CA) surrounding the data collection space. The force plate information was obtained using two force platforms (Advanced Mechanical Technologies Incorporated, Newton, MA). The joint kinematic and kinetics were computed using Euler angles and Newtonian mechanics. For the purpose of this article, running will be described with the major differences highlighted between heel contact and foot flat contact styles. Sprinting, although a natural extension of running with many similarities, will not be discussed.

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Table 1. COMPARISON BETWEEN THE WALKING AND RUNNING TEMPORAL AND STRIDE VARIABLES

<table>
<thead>
<tr>
<th>Variable</th>
<th>Walking</th>
<th>Running</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stance (% gait cycle)</td>
<td>59</td>
<td>43</td>
</tr>
<tr>
<td>Swing (% gait cycle)</td>
<td>41</td>
<td>57</td>
</tr>
<tr>
<td>Step length (cm)</td>
<td>53</td>
<td>63</td>
</tr>
<tr>
<td>Stride length (cm)</td>
<td>106</td>
<td>126</td>
</tr>
<tr>
<td>Cycle time (sec)</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Cadence (steps/min)</td>
<td>134</td>
<td>213</td>
</tr>
<tr>
<td>Velocity (cm/sec)</td>
<td>117</td>
<td>223</td>
</tr>
</tbody>
</table>

GAIT CYCLE EVENTS AND TEMPORAL AND STRIDE VARIABLES

The gait cycle is the period from initial contact of one foot to the following initial contact of the same foot. It is generally divided into the stance (ST) and swing (SW) phases with ST usually representing 60% and SW 40% of the gait cycle in normal walking. A very useful terminology to define the individual events of the gait cycle in normal walking has been described by Perry.¹⁹ The stance phase (Fig. 1A) begins with the instantaneous event of initial contact (IC) and is divided into four subphases: loading response (LR), midstance (MST), terminal stance (TST), and preswing (PSW). The swing phase, which begins with the instantaneous event of toe-off (TO) and ends with IC, is divided into three subphases: initial swing (ISW), midswing (MSW), and terminal swing (TSW). The events of the gait cycle are generally very useful when describing pathological gait. They can allow the clinician focus on specific points in the gait cycle and help improve communication when describing pathology.

Normal walking also may be defined in terms of the double support and single support times. Double support, when the two limbs are in contact with the ground, occurs at the first and last 10% of stance phase or LR and PSW respectively. Single support, when one foot is in contact with the ground, is equal to the SW time of the opposite limb.

Other variables commonly used to describe normal gait are cadence, stride length, and step length. Cadence is the number of steps per unit time. Stride length is the distance from initial contact of one foot to the initial contact of the

Table 2. COMPARISON BETWEEN THE AVERAGE WALKING AND RUNNING VERTICAL AND FORE-AFT GROUND REACTION FORCE PATTERNS

<table>
<thead>
<tr>
<th></th>
<th>Vertical Component (% body weight)*</th>
<th>Fore-Aft Component (% body weight)†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Walking</td>
<td>122 (15)</td>
<td>109 (13)</td>
</tr>
<tr>
<td>Running</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Mean (± 1 SD)</td>
<td>134 (34)</td>
<td>195 (17)</td>
</tr>
</tbody>
</table>

*In the vertical direction, A and B refer to the first and second peaks, respectively.
†In the fore-aft direction, A refers to the breaking force and B to the propulsion force. During running, the breaking force is divided into two peaks A1 and A2.
Figure 1. A comparison of the gait cycle terminology used for (A), walking and (B), running.
opposite foot. Step length is the distance from initial contact of one foot to initial contact of the same foot.

In pathologic gait, there are generally significant variations in these parameters with respect to normal gait. With increasing pathology, the velocity and cadence usually decrease. Also, the ST phase portion of the gait cycle increases with a corresponding decrease in the SW phase, and step and stride lengths decrease. These parameters, which give an indication of functional ability and are generally easy to measure, are outcome measures and do not increase our knowledge either of the cause or how to correct a specific pathology.

Running is generally described or defined by velocity, which is the ultimate indicator of performance not only for the casual runner but for the elite athlete. Running, however, is not differentiated from walking by velocity but by whether a person becomes airborne. This is determined by the duration of the stance phase as a percentage of the gait cycle. In running, there are two periods of float, that is, when neither foot is in contact with the ground. Therefore, the stance phase must represent less than 50% of the gait cycle and correspondingly, the swing phase must represent greater than 50% of the gait cycle. Generally, with increasing velocity there is a reduction in the stance time and associated increase in swing time. In speed walking, increased velocity is possible through increasing range of motion of the pelvis and trunk.

During running, the gait cycle (Fig. 1B) may be divided into specific events defined by the motion of the lower extremities. As in walking, the gait cycle is initially divided into stance and swing. The ST phase is then divided into two subphases, absorption and propulsion which are separated by MST, and the swing phase into two subphases of initial SW and terminal SW which are separated by MSW. At the beginning and the end of SW phase are the periods of double float, when no foot is in contact with the ground. The duration of the ST and SW phases depends on the running velocity with decreasing ST and increasing SW times with increasing velocity.

Most of the temporal and stride variables are interrelated. For example, increasing velocity is achieved initially through increasing step lengths followed by increasing cadence. As velocity increases there is an increase in the nonsupport or float time. Stride length is a function of leg length and height as well as a function of ability with increasing stride length associated with increasing velocity.

MUSCLE ACTIVITY

Muscle activity during normal walking and running has been well documented. The typical normal walking and running muscle activity is plotted in Figure 2. With increasing velocity in both running and walking there is increasing joint range of motion that is produced by increasing amplitude of muscle activity. The increasing muscle activity is also needed to respond to the increasing external forces experienced during running. There are also changes in the phasic activity of the major muscle groups that reflect the changes in movement patterns when comparing walking with running. The majority of the major muscle groups are active during TSW and ST except for the hip flexors and adductor longus. At TO, the majority of muscles are inactive except for the adductor longus and iliacus. Although the activity of the major muscle groups is discussed in detail in the kinetics section, some of the differences in phasing are highlighted in this section.
Figure 2. A comparison of the typical muscle activation patterns for selected muscles during walking and running. Muscle activity is represented by the solid bars in relation to the gait cycle (stance followed by swing phase).
Quadriiceps

In normal walking, quadriiceps activity is highly variable stride to stride and across people. The quadriiceps is generally active during LR and in TSW with minimal and variable activity at TO. The component active at TO is the rectus femoris and not the vasti. In running, however, this muscle group is highly active in the absorption phase. This is to respond to the greater requirements of weight acceptance and the rectus femoris component also highly active around TO to prevent excessive knee flexion. Activity in TSW is similar in walking and running.

Hamstrings

Similar activity patterns are seen in these two muscle groups with increased amplitudes seen during running as compared with walking.

Anterior Tibialis

The primary difference seen in this muscle group is during the initial part of the gait cycle. Activity of this muscle group during running depends on the type of running style with greater activity seen in heel contact running versus foot flat contact running. Also, peak levels of activity are greater at TO in running as compared with walking.

Gastrocnemius/Soleus

During running, the onset of activity of these muscles occur in TSW and continues throughout ST. This is necessary in both heel contact and foot flat contact runners as a significant level of force generation is required from this muscle in early ST. In normal walking, activity for this muscle begins after LR with no activity seen in SW. Activity of the gastrocnemius/soleus in both walking and running terminates at the end of ST.

JOINT KINEMATICS

Joint kinematics refer to the variables that describe the spatial movement between segments such as joint angular motion measured in degrees. Most of the motion that occurs during normal walking occurs in the sagittal plane (plane that divides the body into the right and left sides). In running, however, one generally observes greater range of motion (ROM) not only in the sagittal plane but in the coronal and transverse planes as well. As velocity increases, greater joint ROM is seen in both walking and running. The mean joint kinematic patterns for normal walking are presented in Figure 3. The specific ranges, mean peak values, and motion direction for the pelvis, hip, knee, and ankle are given for the three planes of motion. The following examination of the joint kinematic plots allows the reader to appreciate the pattern of movement as well as the timing of specific events that are critical to normal walking.
Walking Sagittal Plane

1. Pelvic Motion:
   - **Stance**
     - LR = posterior movement
     - MST/TST = anterior movement
     - PS = posterior movement
   - **Swing**
     - ISW = posterior movement
     - MSW = anterior movement
     - TSW = posterior movement
   - ROM = 4 deg
2. Hip Motion:
   Stance
   - LR/MST/TST = extension (35 deg of flexion–6 deg of extension)
   - PS = flexion (6 deg of extension–0 deg)
   Swing
   - ISW/MSW = flexion (0 deg–37 deg of flexion)
   - TSW = minimal extension (37 deg of flexion–35 deg of flexion)
   ROM = 43 deg

3. Knee Motion:
   Stance
   - LR = flexion (8 deg of flexion–15 deg of flexion)
   - MST/TST = extension (15 deg of flexion–8 deg of flexion)
   - PS = flexion (8 deg of flexion–35 deg of flexion)
   Swing
   - ISW = flexion (35 deg of flexion–64 deg of flexion)
   - MSW = extension (64 deg of flexion–35 deg of flexion)
   - TSW = extension (35 deg of flexion–8 deg of flexion)
   ROM = 60 deg

   Both the degree and the timing of peak knee flexion in SW are critical for SW phase clearance, which is only a few millimeters. The timing of peak knee flexion in SW is at the end of ISW or about 30% of the SW phase. The timing of specific events is very difficult to appreciate through visual observation of gait.

4. Ankle Motion:
   Stance
   - LR = plantar flexion (5 deg of plantar flexion–6 deg of plantar flexion)
   - MST/TST = dorsiflexion (6 deg of plantar flexion–12 deg of dorsiflexion)
   - PS = plantar flexion (12 deg of dorsiflexion–7 deg of plantar flexion)
   Swing
   - ISW = continued plantar flexion (7 deg of plantar flexion–18 deg of plantar flexion)
   - MSW = dorsiflexion to neutral (18 deg of plantar flexion–3 deg of dorsiflexion)
   - TSW = minimal plantar flexion (2 deg of dorsiflexion–5 deg of plantar flexion)
   ROM = 30 deg

Ankle Rockers
   First rocker = plantar flexion (LR)
   - eccentric contraction dorsiflexors
   - controlled lowering of foot to floor
   Second rocker = dorsiflexion (MST/TST)
   - eccentric contraction plantar flexors
   - control of forward motion of shank over foot
   Third rocker = plantar flexion (PS)
   - concentric contraction plantar flexors
   - ankle plantar flexion

The ankle rocker terminology is useful for describing both normal walking and pathologic gait and helps define goals for treatment through the restoration of the rockers.
Coronal Plane

1. Pelvic Motion:
   Stance
   • LR = ST limb pelvis rises 4 deg
   • MST/TST/PS = ST limb pelvis drops 7 deg
   Swing
   • ISW = ST limb pelvis continually drops 1 deg
   • MSW/TSW = ST limb pelvis rises 8 deg
   Neutral position twice in gait cycle; ROM = 8 deg

2. Hip Motion:
   Stance
   • LR = adduction (2 deg of adduction–6 deg of adduction)
   • MST/TST/PS = abduction (6 deg of adduction–4 deg of abduction)
   Swing
   • ISW = abduction (4 deg of abduction–7 deg of abduction)
   • MSW/TSW = adduction (7 deg of abduction–2 deg of adduction)
   ROM = 13 deg

Tranverse Plane

1. Pelvic Motion:
   Stance
   • LR/MST = internally rotated 4 deg
   • TST/PS = externally rotates 8 deg
   Swing
   • ISW/MSW = gradually internally rotates 4 deg
   • TSW = continually rotates 4 deg
   Neutral position twice in gait cycle
   ROM = 8 deg

2. Hip Motion:
   Stance
   • LR = internally rotates 5 deg
   • MST/TST = internally rotated 4 deg
   • PS = externally rotates 4 deg
   Swing
   • ISW = continually externally rotates 3 deg
   • MSW/TSW = oscillates external to neutral position eight
   ROM = 8 deg

3. Foot Progression:
   Stance
   • LR/MST/TST = progressive external rotation 8–10 deg
   • PS = internally rotates 4 deg
   Swing
   • ISW/MSW = externally rotates 12 deg
   • TSW = internally rotates 4 deg
   ROM = 6 deg

During running, there is generally an increase in the dynamic ROM at the ankle, knee, hip, and pelvis in comparison to walking (Table 3). An example of
<table>
<thead>
<tr>
<th>Variable</th>
<th>Walking</th>
<th>Running</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hip</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion (IC)</td>
<td>34 (6)</td>
<td>47 (7)</td>
</tr>
<tr>
<td>Flexion (TO)</td>
<td>-5 (5)</td>
<td>4 (5)</td>
</tr>
<tr>
<td>Range of motion</td>
<td>47 (4)</td>
<td>48 (6)</td>
</tr>
<tr>
<td><strong>Knee</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion (IC)</td>
<td>8 (5)</td>
<td>24 (6)</td>
</tr>
<tr>
<td>Peak flexion (LR)</td>
<td>21 (7)</td>
<td>47 (4)</td>
</tr>
<tr>
<td>Peak flexion (SW)</td>
<td>65 (6)</td>
<td>82 (6)</td>
</tr>
<tr>
<td>Range of motion</td>
<td>60 (7)</td>
<td>63 (8)</td>
</tr>
<tr>
<td><strong>Ankle</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle (IC)</td>
<td>-1 (4)</td>
<td>2 (4)</td>
</tr>
<tr>
<td>Peak dorsiflexion (ST)</td>
<td>14 (3)</td>
<td>25 (5)</td>
</tr>
<tr>
<td>Peak plantar flexion</td>
<td>-17 (7)</td>
<td>-17 (11)</td>
</tr>
<tr>
<td>Range of motion</td>
<td>31</td>
<td>42</td>
</tr>
</tbody>
</table>

All angles are measured in degrees. At the ankle, a negative angle denotes plantar flexion and a positive angle dorsiflexion. (IC = initial contact; TO = toe-off; LR = loading response; SW = swing; ST = stance)

The kinematic patterns for the pelvis, hip, knee, and ankle during running are described in the next section and plotted in Figure 4. These data represent running patterns for a medium running speed. Increased peak values and ROM would be expected with increased velocities. As mentioned previously, this change in peak values and ROM is possible through increased muscular activity and is consistent with greater step and stride lengths.

Sagittal Plane

1. **Pelvic Motion:**
   - Stance
     * absorption = posterior movement
     * propulsion = anterior movement
   - Swing
     * T5W = posterior movement
     * T5SW = anterior movement
   - ROM = 7 deg

2. **Hip Motion:**
   - Stance
     * absorption/propulsion = extension (50 deg of flexion–5 deg of flexion)
   - Swing
     * initial swing = flexion (5 deg of flexion–52 deg of flexion)
     * terminal swing = minimal extension (52 deg of flexion–50 deg of flexion)
   - ROM = 46 deg

3. **Knee Motion:**
   - Stance
     * absorption = flexion (16 deg of flexion–40 deg of flexion)
     * propulsion = extension (40 deg of flexion–20 deg of flexion)
Figure 4. The mean joint kinematics for the pelvis, hip, knee and ankle in the coronal, sagittal and transverse planes during heel contact running. The format used for this figure is similar to the one in Figure 3.

Swing
- initial swing = flexion (45 deg of flexion–79 deg of flexion)
- terminal swing = extension (79 deg of flexion–16 deg of flexion)
ROM = 63 deg

4. Ankle Motion:
   Stance
   - absorption = dorsiflexion (0 deg–24 deg of dorsiflexion)
   - propulsion = plantarflexion (24 deg of dorsiflexion–3 deg of plantar flexion)
Swing
- initial swing = dorsiflexion (3 deg of plantar flexion–3 deg of dorsiflexion)
- terminal swing = minimal plantarflexion (3 deg of dorsiflexion–0 deg)
ROM = 56 deg
Coronal Plane

1. Pelvic Motion:
   Stance
   • absorption/propulsion = minimal motion
   Swing
   • initial swing/terminal swing = minimal motion
   ROM = 2 deg

2. Hip Motion:
   Stance
   • absorption = adduction (6 deg of adduction–8 deg of adduction)
   • propulsion = abduction (8 deg of abduction–2 deg of abduction)
   Swing
   • initial swing = abduction (2 deg of adduction–8 deg of abduction)
   • terminal swing = adduction (8 deg of abduction–6 deg of adduction)
   ROM = 14 deg

Transverse Plane

1. Pelvic Motion:
   Stance
   • absorption/propulsion = internally rotates (8 deg externally–8 deg internally)
   Swing
   • initial swing/terminal swing = externally rotates (8 deg internally–8 deg externally)
   Neutral position twice in gait cycle
   ROM = 16 deg

2. Hip Motion
   Stance
   • absorption = minimal internal rotation
   • propulsion = minimal external rotation
   Swing
   • initial swing/terminal swing = minimal internal rotation
   ROM = 8 deg

3. Foot Progression:
   Stance
   • absorption = progressive external rotation (10 deg externally–12 deg externally)
   • propulsion = internally rotates (12 deg externally–0 deg)
   Swing
   • initial swing = externally rotates (0 deg–14 deg externally)
   • terminal swing = internally rotates (14 deg externally to 10 deg externally)
   ROM = 14 deg

JOINT KINETICS

Joint kinetics refer to the forces that cause motion such as the ground reaction forces, the joint moments, and joint powers. These parameters can provide more insight into the causes of movement gait abnormalities as compared with
joint kinematics. Joint kinetics are calculated through the simultaneous collection of positional information (joint kinematics) and the ground reaction forces as measured with a force plate. The actual calculations are made using Newtonian mechanics, not the resultant ground reaction force method. Joint kinetics are not visual as are joint kinematics and thus are less intuitive and more difficult to interpret. Therefore, before continuing, the joint kinetic parameters that are used to describe walking and running are defined.

Ground reaction forces are the forces exerted by the ground on the foot during foot contact. The resultant ground reaction force has three component forces: the fore-aft, medial-lateral, and the vertical. The vertical and largest component during gait resembles the resultant ground reaction force in shape. The point of action of these forces is at the center of pressure on the bottom of the foot. These forces are measured using a force plate.

The net joint moment reflects the body's response to an external load and indicates which muscle group is dominant. The external loads during normal walking and running include the ground reaction forces, the mass, and the mass moments of inertia of the body segments. The body response refers to the muscle moments needed to counteract the external loads to provide support and progression. In the figures presented in this article the internal or muscle moments are indicated on the plots. As a result, the moments presented correspond with the muscle activity as measured through dynamic electromyography (EMG). The definition of a moment is the product of a force and the distance to line of action of the force from a center of rotation. In relationship to the human body, the force is produced by the muscle that is acting at a distance from the center of rotation of the joint. Moments may also be produced by ligaments and joint contractures as seen in certain pathology. The net joint moment is usually represented as flexor or extensor depending on the joint described. As the moment value presented is a net value (i.e., it incorporates the effect of the agonist and antagonist muscle groups) it does not suggest that the muscle acting on the opposite side of the joint is silent but indicates which muscle group is dominant. Dynamic EMG is the only method of determining if the non-dominant muscle group is active.

The net joint power is the product of the joint angular velocity and the joint moment. This quantity represents the rate of doing work and is usually described as power generation and power absorption. The net joint power is related to the type of muscle contraction, with a net power absorption occurring during an eccentric muscular contraction (lengthening under tension) and a net power generation occurring during a concentric muscular contraction (shortening under tension). In short, a muscle will have a net power generation when the contraction when it produces a motion in the same direction of its pull. Power generation is necessary for forward progression. This parameter can provide interesting insight into the mechanisms of how a person with gait pathology is moving forward.

**Ground Reaction Force Patterns in Running and Walking**

The shape and amplitude of the component ground reaction forces are characteristic of the type of ambulation. During normal walking, the vertical and largest ground reaction force is "double bump" in shape and reaches peak values ranging from 1.3 to 1.5 times the body weight. These peaks occur during LR and push off (Fig. 5). During running, the vertical ground reaction force begins with a small impact force peak in the first 20% of stance followed by a more gradual
Figure 5. A comparison of the vertical ground reaction force patterns for (A), running and (B), walking from a representative subject. The ground reaction forces are represented as a percentage of body weight.

and larger active peak in the remainder of stance (Fig. 5). The magnitude of this force, which ranges from 2 to 3 times body weight in this study, was significantly greater than walking.15

The fore-aft component of the ground reaction force during walking indicates breaking in the first half of ST followed by propulsion in the last half of ST. The peak amplitudes of these forces is about 30% of body weight. During running there is usually an additional breaking force that occurs at about 10% of the stance phase. The breaking and propulsion proportions, of the stance phase and also the peak amplitudes are similar in running as compared with walking.

The medial and lateral component of the ground reaction force in both walking and running represent a very small portion of the body weight (10%) in the subjects tested. These values are similar to those reported by Roy21 ranging from 10% to 20%. The shape of these curves also tends to be more variable.

It is important to note that the shape of the ground reaction force patterns depend primarily on the running style,3,31 for example, heel-toe or foot-flat styles. Variability in amplitude of the ground reaction force patterns depends on veloci-
ity with increasing velocities associated with increased peak force amplitudes. The subjects included in this study had heel contact running styles with the center of pressure path beginning on the rear lateral border of the foot and continuing along the lateral border to the center of the forefoot where it remained for approximately two thirds of the ST phase. For midfoot strikers the center of pressure begins on the lateral midfoot and progresses posteriorly as the rear of the foot comes in contact with the ground. The center of pressure then moves rapidly to the forefoot and remains there for the majority of the ST phase.

Typical Joint Kinetic Patterns During Walking

Joint kinetic patterns during walking show minimal intrasubject variability in terms of modulation or shape of the curves. There is some variability in the peak amplitudes relating to walking velocity, with increasing peak moment and power values with increasing velocities. The mean joint kinetic patterns for the sagittal plane during walking are presented in Figure 6. The description of these patterns is included below.

Sagittal Plane

During LR, MST and TST there is a net hip extensor moment as the hip extends to bring the body center of gravity to its highest position in single limb

Figure 6. The mean (±1 standard deviation) sagittal plane joint kinematics (top row), moments (middle row), and powers (bottom row) for the ankle, knee, and hip during walking.
stance. This a concentric muscular contraction and thus a power generation. During TST, there is a net power absorption with lengthening of anterior capsule which decelerates hip extension. In PSW, the hip begins to flex under eccentric control of the hip flexors producing power to help advance the ST limb into SW. In ISW, the hip continues to flex under the concentric contraction of the hip flexors to advance the limb into SW and provide SW phase clearance. Peak hip flexion is terminated in MSW with slight extension in TSW under concentric contraction of the hip extensors.

During LR, the knee flexes slightly under eccentric control of the knee extensors which help in weight acceptance. This followed by knee extension under concentric control of the knee extensors in MST. In the majority of TST, there is a net knee flexor moment under eccentric control of the gastrocnemius which begins the process of aiding the advancement of the ST limb into SW. In PSW, there is minimal extensor moment under eccentric control of the rectus femoris. The knee moment in ISW and MSW is minimal. In TSW, there is a net knee flexor moment under eccentric control to decelerate knee extension in preparation for initial contact.

During LR at the ankle, there is a net dorsiflexor moment as the anterior tibials contract eccentrically to control the lowering of the foot to the floor. This is also known as first rocker. In MST, there is a net ankle plantar flexor moment as the ankle plantar flexors contract eccentrically to control the forward progression of the shank over the plantigrade foot. This is also known as second rocker. In TST and PSW, there is a continued net plantar flexor moment as the ankle plantar flexors contract concentrically to aid in advancement of the stance limb into swing. This is commonly known as push-off or third rocker. In ISW, the ankle continues to plantar flex slight after which dorsiflexion occurs under concentric control of the ankle dorsiflexors. The net joint moment and power at the ankle in the swing phase are negligible owing to the small mass and inertial characteristics of the foot.

Coronal Plane

During normal walking, motion occurs primarily at the hip in the coronal plane. Because of the minimal motion at the knee and ankle, current measurement techniques are not sufficient to describe motion in this plane because of the signal to noise ratio. In normal gait, the hip abducts under eccentric control of the dominant hip abductor muscle group. This helps weight acceptance and controls the drop of the opposite hemipelvis. In MST, the hip abducts under concentric contraction of the dominant hip abductors to help elevate the opposite hemipelvis and aid in clearance of the swing limb.

Typical Joint Kinetic Patterns During Running

With each style of running, there are typical joint kinetic patterns. For example, a heel-toe style of running is associated with a dorsiflexor moment during the initial part of the stance phase. As in walking, the peak amplitudes of the joint moments and powers increase with increasing velocities. The typical joint moments and powers for the sagittal hip, knee, and ankle are presented in Figure 7. The description of the these patterns is included next. Generally, there are increased amplitudes of the peak joint kinetics in running as compared to walking (Table 4).
Sagittal Plane

During the absorption and propulsion phase, the hip continuously extends initially under the concentric control of the hip extensors, followed by the eccentric control of the hip anterior capsule and hip flexors. In the ISW phase, the hip flexes as a result of the concentric contraction of the dominant hip flexors. In TSW, the hip terminates flexion and then extends under the concentric control of the hip extensors. Unlike walking, in running, the highest point of the center of gravity is in the SW phase and the lowest point in the ST phase.

During absorption, the knee flexes under eccentric control of the knee extensors to control the height of the body center of gravity. This is followed by knee extension under concentric control of the knee extensors in the propulsion phase. In ISW, through eccentric contraction of the rectus femoris there is a small net knee extensor moment that controls excessive knee flexion. In TSW, the knee rapidly extends initially through inertia and is slowed in the later part of TSW through eccentric contraction of the dominant knee flexors.

Ankle joint kinetics at LR vary, depending on the style of running. Those persons demonstrating a heel contact pattern generally show a small dorsiflexor moment in the initial part of stance, followed by a net plantar flexor moment for the remainder of the absorption phase. People who have a foot flat contact show...
Table 4. COMPARISON BETWEEN SELECTED MEAN (± 1 STANDARD DEVIATION) WALKING AND RUNNING JOINT MOMENTS AND POWERS FOR THE SAGITTAL AND CORONAL PLANES

<table>
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<tr>
<th>Variable</th>
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</tr>
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<td>Sagittal Plane</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hip</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max extensor moment (initial stance)</td>
<td>0.72 (0.30)</td>
<td>1.59 (0.59)</td>
</tr>
<tr>
<td>Max power generation (initial stance)</td>
<td>0.61 (0.31)</td>
<td>2.34 (1.75)</td>
</tr>
<tr>
<td>Max power generation (at toe-off)</td>
<td>0.78 (0.27)</td>
<td>1.98 (0.88)</td>
</tr>
<tr>
<td><strong>Knee</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max extensor moment (initial stance)</td>
<td>0.53 (0.22)</td>
<td>1.41 (0.24)</td>
</tr>
<tr>
<td>Max power generation (stance)</td>
<td>0.59 (0.36)</td>
<td>1.41 (0.24)</td>
</tr>
<tr>
<td>Max power absorption (stance)</td>
<td>-1.05 (0.55)</td>
<td>-5.36 (1.14)</td>
</tr>
<tr>
<td><strong>Ankle</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max plantar flexor moment (terminal stance)</td>
<td>1.26 (0.22)</td>
<td>1.72 (0.31)</td>
</tr>
<tr>
<td>Max power generation (terminal stance)</td>
<td>3.49 (1.03)</td>
<td>9.56 (3.10)</td>
</tr>
<tr>
<td>Max power absorption (stance)</td>
<td>-0.79 (0.32)</td>
<td>-5.13 (1.47)</td>
</tr>
<tr>
<td>Coronal Plane</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hip</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max abductor moment (stance)</td>
<td>0.62 (0.14)</td>
<td>0.91 (0.34)</td>
</tr>
<tr>
<td><strong>Knee</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max abductor moment</td>
<td>0.36 (0.14)</td>
<td>0.53 (0.28)</td>
</tr>
</tbody>
</table>

All joint moment units are Nm/kg and joint power units are W/kg.

rapid dorsiflexion of the ankle under eccentric control of the ankle plantarflexors (no dorsiflexor moment). This aids in shock absorption and contributes to the decrease in the height of the body center of gravity. In the propulsion phase, the ankle plantar flexes rapidly under concentric control of the ankle plantar flexors. This aids in propulsion of the ST limb into SW and the double float. During ISW, the ankle dorsiflexes under concentric control of the ankle dorsiflexors. As in walking, the net joint moment and power at the ankle is negligible.

**Coronal Plane**

Hip joint kinetic patterns in walking and running are similar in the coronal plane. Because of the increased forces there are increased amplitudes in running as compared with walking (Table 4). In general, during running, absorption is followed by generation as the hip abductors control the position of the pelvis and contribute to weight acceptance. The hip continues to abduct in ISW and adduct in TSW owing to movement of the pelvis controlled by the stance limb hip abductors.
Relationship Between Power Absorption and Generation

A comparison of the power absorption and generation at the hip and knee during running illustrates the consistent reversal of power at these joints (Fig. 8). For example, during the ISW phase, the knee absorbs energy during flexion at the same time the hip generates energy during flexion. These motions are both controlled by the double joint rectus femoris muscle that contracts eccentrically at the knee and concentrically at the hip. Similarly, in TSW the knee absorbs energy during extension at the same time the hip generates energy during hip extension. These motions are controlled by the double joint hamstring muscles that contact eccentrically at the knee and concentrically at the hip, allowing efficient energy transfer between joints. The dual role of the hamstring muscles has been previously described by Mann and Winter. This type of energy transfer is not as evident during walking.

ENERGY

As described previously, both walking and running involve alternate breaking and accelerating with a resulting rise and lowering of the center of gravity. During walking, the center of gravity is in its lowest position during the periods of double support when the body is moving the slowest and highest during the period of single support when the body is moving the fastest. The potential energy is therefore highest during single support when the kinetic energy is the lowest and lowest during double support when the kinetic energy is the highest.

![Figure 8. A comparison of the mean joint powers for the hip (dark line) and knee (light line) during running. Throughout the gait cycle the power is either generated at the knee and simultaneously absorbed at the hip or absorbed at the knee and simultaneously generated at the hip. This demonstrates the most efficient use of the double joint muscles crossing these joints, that is, the rectus femoris and the hamstrings.](image-url)
As a result, the energy cost of walking is relatively low. During running, the center of gravity is at the highest point when the body is in double float at which time the kinetic energy is the highest. The center of gravity is at its lowest point during the absorption phase when the kinetic energy is the lowest. During running, however, energy is stored as elastic strain energy that is released during push-off.  According to Cavanagh, 950% of the total work performed is through the return of elastic energy. During running, power generation or concentric work is always preceded by power absorption or eccentric work (see Fig. 7). As discussed previously, the double joint muscles contribute to this energy saving mechanism.

SUMMARY

An increased knowledge of the biomechanics of normal walking and running will improve our understanding of the possible mechanisms of pathology and ultimately improve the treatment of pathology and injury. Running, a natural extension of walking, involves increased velocities, joint range of motion, forces, muscle activity, joint moments, and joint powers as compared with walking. These differences not only stress the mechanics of the body to a greater extent but also contribute to the development of injury due to overuse. With the use of modern computerized gait analysis techniques that provide objective information, comprehension of normal and also pathologic walking and running patterns can be improved.

References

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