The purpose of this descriptive study was to quantify the work that is accomplished by major muscle groups of the affected limb of 10 children with spastic hemiplegia secondary to cerebral palsy during walking. Cinematographic film and force-plate data were used in a biomechanical link-segment model to calculate the positive and negative work performed by the muscles around each joint. The results revealed that the ankle plantar flexors produced just over one third of the positive work for the affected limb instead of the normal two thirds. The greatest proportion of positive work was performed by the hip muscles. More research using work and power analyses will assist in prescribing and determining the effectiveness of treatments. [Olney SJ, MacPhail HEA, Hedden DM, Boyce WF. Work and power in hemiplegic cerebral palsy gait. Phys Ther. 1990;70:431-438.]

Key Words: Biomechanics; Cerebral palsy; Gait; Muscle performance, measurement.

Gait analysis of children with cerebral palsy (CP) has been used to study the basic biomechanics of their walking, which, in turn, has assisted in therapeutic and surgical decision making. Recent developments in the technology used in gait analysis and the ready availability of high-speed computers at modest cost have made possible certain analyses that were known but not feasible. One of these analyses is the determination of instantaneous power and work accomplished by the muscle groups crossing major joints.

To understand the method, walking should be regarded as movement that occurs only if work is done on its parts, the limbs. Positive work is accomplished when concentric contractions are performed by muscles. The other form of work is done against gravity or other external forces and is called negative work. Negative work is accomplished when eccentric contractions are performed. In an activity such as walking, the energy level of the body returns to about the same level at the same point in the gait cycle for each succeeding stride, but successive "additions" (positive work) and "removals" (negative work) occur in patterns that are now known. It is important to emphasize that we are not implying a "zero sum" of energy usage in a metabolic sense, but a mechanical distinction that has classically been used to describe muscle function.

Mechanical work is defined as the product of force acting through a distance, or, in the case of rotatory motion that the limbs perform in walking, the product of the moment of force (torque) and angular displacement. When a muscle exerting tension shortens, work is done on the muscle's attachments and the muscle is doing positive work. That is, energy is being generated by the muscle. When muscle is stretched by a load that exceeds the tension the muscle is generating, however, work is done on the muscle and the muscle is doing negative work. This transfer of energy to the muscle, referred to as absorption, is usually followed by its degradation into heat.

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Power is the rate of doing work, or the work divided by the time interval concerned. The work done over a gait cycle by the muscles crossing any given joint can be calculated by first determining the net power at many points of the gait cycle and the time intervals between them. It is a simple matter to determine the time intervals involved, for example, the intervals between the frames of a cinematographic film of the gait cycle. Derivation of the instantaneous powers about each joint requires knowledge of the net moments about the joints and the velocity of angular movement of the adjacent parts. To do this, cinematographic film and force-plate data are taken simultaneously from the walking subject. Data from both sources are then used in a mathematical model to calculate the power at lower extremity joints, a process that is more fully described below.

The power (P) of a muscle group at a joint (j) at a given instant in time is calculated using the formula:

\[ P_j = M_j \cdot \omega_j \]

where \( M_j \) is the net moment of force at \( j \) and \( \omega_j \) is the joint angular velocity. By convention, \( P_j \) is positive if \( M_j \) and \( \omega_j \) are of the same sign (i.e., in a concentric contraction) and \( P_j \) is negative if \( M_j \) and \( \omega_j \) are of opposite signs (i.e., in an eccentric contraction). The amount of positive and negative work can be calculated by mathematically integrating the power curve over the time period of interest, in this case, one stride. For the purposes of this article, we will use the terms concentric work during the positive power phases when positive work is being done and eccentric work during negative power phases when negative work is accomplished.

Calculations of mechanical power were pioneered by Elftman,10,11 although the limited available technology and the author's hand calculations produced crude results. Other techniques, such as those of Cavagna and Margaria,12 have had serious methodological limitations. More recently, Elftman's early work has been replicated and validated by balancing the joint and muscle powers with the rate of change of segmental energies.13

The most comprehensive information on work and power in normal walking has been reported by Winter.7,14,15 In his studies, three healthy adult groups of 14 to 19 subjects each walked at three cadences: slow (mean cadence, 85 steps/min), natural (mean cadence, 105 steps/min), and fast (mean cadence, 122 steps/min). The results from the natural speeds are shown in Figure 1. The major phases will be described here. The ankle showed a phase of eccentric work by the plantar flexors during most of the first 40% of the gait cycle (A1), followed by a large phase of concentric work at push-off (A2). The knee had three phases attributable to knee extensor activity: one of eccentric work at weight acceptance (K1), a small concentric period during midstance (K2), and a large eccentric phase at push-off and early swing (K3). A fourth phase (K4) occurred at the end of swing and was caused by the knee flexors acting eccentrically. Note that only one small phase of concentric work was performed by the muscles around the knee. The hip showed a small amount of concentric work by the extensors in early stance (H1), low eccentric flexor work during much of the rest of stance (H2), and a substantial period of concentric flexor work in late stance and early swing (H3) ("terminal stance and pick-up" or "pull-off"). A very small concentric phase by the extensors at the termination of the swing phase (H4) is sometimes identifiable. Because the plotting scales have been kept constant, the amount of work is represented in Figure 1 by the area under each of the curves.

It is clear that most of the positive work of walking is produced by the ankle plantar flexors during the A2 phase and that a smaller contribution is made by the hip flexors at pull-off. Of minor importance are the inputs of the hip extensors and the knee extensors in the early stance phase. Comparable power phases were reported by Cappozzo and colleagues,16 who calculated the lower limb muscle work of five subjects. Similar power patterns are characteristic of treadmill walking,17 although somewhat different methodology and differences between overground and treadmill walking precluded their direct use in this study. No reports of children have appeared to date, although some are expected in the near future (JR Gage, personal communication).

Knowledge of the power patterns and amounts of work performed by major muscle groups of the affected limb of children with hemiplegia secondary to CP would assist in understanding of their primary gait deficiencies and hopefully in identification of possible compensations. The purpose of this descriptive study, therefore, was to quantify the work that is accomplished by major muscle groups of the affected limb of 10 children with spastic hemiplegia secondary to CP during walking.

Method

Subjects

Ten children (7 boys, 3 girls) with spastic hemiplegia secondary to CP were studied in the Human Motion Laboratory of the School of Rehabilitation Therapy at Queen's University (Kingston, Ontario, Canada). Using the classification of Winters and colleagues,18 all subjects belonged to the minimally affected Group 1. The subjects' ages ranged from 5.0 to 11.8 years (Table 1). Informed consent was provided by each subject's parent(s) or legal guardian(s). Two children had heel-cord lengthening more than 4 years previously, but neither had dorsiflexion during gait that exceeded 5 degrees.

Procedure

Reflective markers were placed on the following landmarks: the camera-side fifth metatarsal joint, the heel, the ankle lateral malleolus, the lateral epicondyle of the femur, the greater trochanter at the hip joint level, and the acromioclavicular joint. All children
walked barefoot and independently at their comfortable, natural cadence with the more affected side nearest the camera while three good strides were collected. A tracking cart with a cinematographic camera\(^*\) (50 frames/sec [50 Hz]) was guided manually on a track beside the walkway at a distance of 480 cm. Background markers on the wall beside the walkway provided a reference so that the body coordinates could be scaled later and represented as absolute coordinates. At the same time, force-plate\(^1\) data were sampled at a frequency of 500 Hz, converted to digital form, and stored on a desktop computer\(^2\) along with a synchronizing signal from the camera. The camera signal simultaneously produced a digital code on each frame of the film that would enable matching of the force-plate data with the correct frame of the film. The force-plate data were smoothed using a double-pass, second-order, 10-Hz, low-pass Butterworth digital filter and used to calculate the vertical and fore-aft shear ground-reaction forces and the center of pressure of the foot-floor force vector. The first record of vertical force above baseline signaled initial contact of the foot with the force plate, and the number of that synchronizing pulse indicated the frame of the film corresponding to initial contact. To assist the person performing film digitization, the digital code appearing in the film corresponding to the event of initial contact was printed on the computer output.

**Data Analysis**

Coordinates of the body and background markers from a stride, including at least six lead-in and trailing frames, were extracted from the cinematographic film using a digitizer\(^3\) interfaced to the desktop computer. Using the background markers as a spatial reference, raw coordinate data were scaled and corrected for parallax error between the plane of progression of the subject and the plane of the background reference markers. The distance between these planes could be determined by the position of the foot with respect to marks on the floor that were visible on the film. The coordinate data were digitally filtered using a cut-off frequency corresponding to the fourth harmonic of the gait-cycle frequency, a selection that was validated by Pezzack et al.\(^19\) A standard seven-segment link-segment model was used in a computer program adapted from Winter\(^10\) to calculate the kinematic and kinetic variables. Although some human error is involved in manually selecting the centers of the reflective markers, the magnitude of this "noise" in this and similar laboratories\(^*\) has been regularly found to be about 1 mm rms (root mean square, or the square root of the average of squared difference values for a series of digitized data points). This magnitude consistently produces test-retest reliabilities in this laboratory greater than .985 (Pearson product-moment correlation) for kinematic data. Anthropometric constants, including segmental inertias, were obtained from Jenson\(^20\) and based on each subject's body weight and mass. The instantaneous power of the more affected hip, knee, and ankle joints for each frame of the film was calculated as the product of the net moment and the angular velocity of the joint according to the formula given earlier.

The positive work and negative work performed by the muscles across each joint for each stride were determined by calculating the area under the power curve (ie, mathematically integrating using a computer program) that had been normalized by dividing each value by the subject's body mass.

The proportions of the total positive work and total negative work accomplished by the muscles across each joint were calculated.

**Results**

Figure 2 shows the instantaneous power curves for each joint. Very low levels of positive work occurred at push-off (A2). This deficiency is also reflected in the low mean positive work values reported in Table 2. The ankle plantar-flexion negative work (A1) for the children with CP was small, and there was a small unnamed positive burst during stance that does not usually occur. At the knee, the early negative phase (K1) was small in the children, but the negative work phase at push-off and early swing (K3) was large. The positive work performed by the hip extensors in early stance (H1) was large and continued late into stance. The positive phase (H3) occurring during pull-off (terminal stance and pick-up) also was large. The final burst of positive work (H4) produced by the hip extensors was very large.

Table 2 presents the positive and negative work values for this study. The proportion of total positive and negative work performed by the muscles at each joint are shown in Table 3. In the children with CP, the hip supplied half of the total concentric work, the ankle about a third, and the knee the remainder.

**Discussion**

The limitations of this study must be kept in mind while interpreting results. The data represent the mechanical work that is performed in the sagittal plane at the hip, knee, and ankle joints, but the data do not include mechanical work performed in the frontal plane. Because energy changes in the frontal plane have been reported to be small even in the presence of gait pathologies,\(^21\) this does not appear to be a serious deficiency. In addition, co-contractions and muscle contractions that are performed against a static load do not result in mechanical work. Thus, the

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*LoCam 51, Redlake Corp, 1711 Dell Ave, Campbell, CA 95008.

*Advanced Mechanical Technology Inc, 141 California St, Newton, MA 02158.

*Model 9845, Hewlett-Packard (Canada) Ltd, 2670 Queenview Dr, Ottawa, Ontario, Canada K2B 8K1.

*GTCO Datatizer, GTCO Corp, 1055 First St, Rockville, MD 20850.
numerical values will underestimate true values. The model of the half-body as four linked segments is obviously a simplification and cannot be used to determine subtle contributions across minor joints. When the interpretation and application of work and power analyses have become more developed, a more complex model may be required. A further limitation of this study is the absence of data on healthy children. Although normative data are desirable, however, within-subject changes in joint kinematics after the age of 5 years are minimal.

A discussion of results requires preliminary clarification of the event historically referred to as push-off, or "roll-off." In summary, Perry and associates have claimed that the body advances over the supporting foot with the ankle locked and that the function of the plantar flexors is to allow the tibia and foot to act as a solid unit. Evidence that their function is not static, however, is provided by several authors. Winter found that two thirds of the positive work of walking is performed by the ankle plantar flexors. It is not at first apparent how the plantar flexors can continue to exert force throughout push-off (40%-60% of the gait cycle) when the raw electromyographic recordings are silent at approximately 50% of the cycle. This phenomenon is attributable to "electromechanical delay," or the differences between the time course of the motor action potentials and that of the twitch tension. Not only are peak-to-peak differences between these events in the order of 116 msec (s = 9) for the soleus muscles, but the delay in drop of the tension is even more pronounced than the rise. Hence, the muscle exerts force much longer than is evident in the raw EMG recording.

A second conceptual concern about the term push-off is that the upper body is descending until near toe-off. During this part of its descent, its velocity is negative but values are approaching zero; that is, the upper body is descending, but its speed downward is decreasing. This downward decrease in speed results in a positive, or upward, acceleration consistent with push-off. Perhaps more intuitively persuasive is the fact that the work done by the plantar flexors also occurs concurrently with an increase in velocity of the upper body, which peaks near initial contact.

Fig. 1. Average power patterns of ankle, knee, and hip for 19 healthy subjects walking at mean natural cadence of 105 steps/min. (A1 = eccentric work by ankle plantar flexors; A2 = concentric work at push-off; K1 = eccentric work by knee extensors at weight acceptance; K2 = concentric extensor work during mid-stance; K3 = eccentric extensor work at push-off and early swing; K4 = eccentric work by knee flexors at end of swing; H1 = concentric work by hip extensors in early stance; H2 = eccentric work by hip flexors during mid-stance and late stance; H3 = concentric work by hip flexors in late stance and early swing; H4 = concentric work by hip extensors at termination of swing phase) (Redrawn from Winter.)
Table 1. Subject Characteristics

<table>
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<tr>
<th>Subject Code</th>
<th>Age (yr)</th>
<th>Sex</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Velocity (m/sec)</th>
<th>Cadence (steps/min)</th>
<th>Affected Side</th>
<th>Maximum Dorsiflexion (°)*</th>
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<tr>
<td>Q027</td>
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<td>F</td>
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<td>M</td>
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<td>31</td>
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<td>130</td>
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<td>-45</td>
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<tr>
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<td>1.19</td>
<td>119</td>
<td>R</td>
<td>-13</td>
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<tr>
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<td>F</td>
<td>118</td>
<td>21</td>
<td>1.27</td>
<td>156</td>
<td>L</td>
<td>-45</td>
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<tr>
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<td>M</td>
<td>161</td>
<td>38</td>
<td>1.25</td>
<td>131</td>
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<td>-24</td>
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<td>0.64</td>
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<td>Q114</td>
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<td>M</td>
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<td>20</td>
<td>1.00</td>
<td>128</td>
<td>L</td>
<td>-16</td>
</tr>
</tbody>
</table>

| Mean (X)    | 8.6      | 136  | 27          | 1.10         | 131              | -28               |
| Standard Deviation (s) | 2.6 | 21 | 7.9 | 0.33 | 39 | 13 |

*Maximum voluntary ankle dorsiflexion, knee extended (0° = neutral).

of the contralateral foot in healthy individuals walking at normal speeds. It must also be borne in mind that much of the work performed by the plantar flexors at push-off is required to move the limbs themselves, a function estimated at 80% of the total body work.26

Examination of the important differences between the power curves of hemiplegic children with CP and those of healthy adults7 provides insight into the mechanics of their gait. At slow and normal speeds of walking in healthy subjects, the ankle plantar flexors contribute nearly two thirds of the total concentric work (Table 3). The hip flexors and extensors are responsible for about one quarter of the total concentric work, and the knee extensors the remainder. The low average level of power generation by the ankle plantar flexors in the children with CP is a deficiency of perhaps major importance. As shown in Table 3, the ankle plantar flexors provide only about one third of the total work of the affected limb. The small positive burst during stance that does not usually occur in normal walking is a result of a small “bounce” of plantar flexion during the middle third of stance; this burst is fairly small in most cases and does not appear to be a very important source of positive work.

Berger and colleagues27,28 found plantar-flexor muscle activity during stance in subjects with CP to be much lower than normal, consistent with our finding of low positive work values. In contrast to healthy individuals who show a slow increase in the tension of the Achilles tendon after initial contact corresponding to an increase in plantar-flexor muscle activity, their subjects showed a sharp increase in the tension of the Achilles tendon that did not match plantar-flexor activity. The authors concluded that this increase was caused by mechanical changes in the muscle fibers. Except for solitary biphasic potentials seen in the EMG recordings of gastrocnemius muscles just after initial foot contact, there were no indications of an influence of pathologic reflexes in muscle activity. The studies of Tardieu and colleagues29,30 also suggested alterations in the mechanical properties, which would account for the performance differences we have found.

The low levels of power generated by the ankle plantar flexors at push-off were further diminished by an increased magnitude of the negative work phase of the knee. When positive work occurs at one joint while negative work occurs at another, the effect on the body as a whole is the difference between the two phases. In normal walking, the negative work phase begins a little later than the ankle positive work phase (A2), but overlaps it. As shown in Figure 1, however, in normal walking, the negative work of the knee extensors at push-off and early swing (K3) is much less than the positive work of the ankle plantar flexors at push-off (A2), which results in net increases in the energy of the body at that time. In contrast, in children with CP, the positive and negative work levels were nearly the same. That is, there was excessive removal of the energy (eccentric work) by the knee extensors almost as soon as it was produced by the ankle plantar flexors (concentric work). This is a serious waste of energy for these subjects.

The results suggest that the reduced levels of ankle work resulted in greater amounts of work being done by muscle groups of the hip. The hip flexors produced slightly increased values at pull-off (H3); the hip extensors provided a larger and longer period of positive work during early stance (H1) and a final burst of concentric activity just before initial con-
tact (H4). Although not reported in this study, EMG recordings of the major muscle groups during walking have provided information on co-contraction and verified the findings of the power curves. Simon and colleagues\textsuperscript{31} reported prolonged participation of the gluteal muscles in two groups of unbraced children with CP who had hyperextended knees during the stance phase of their gait and suggested that there was not an obvious kinematic explanation. It is possible that one level of explanation is provided by the evident need for increased positive work.

The data obtained in this study suggest important implications for patient management. First, corrective surgery is commonly performed on all the muscles involved in power production of the legs—the triceps surae muscles, the hamstring muscles, and the hip flexors. Because most surgery decreases the moment-generating ability of the muscle group,\textsuperscript{32} the work the muscle group could accomplish would also decrease. Surgical decisions are particularly crucial in slow-walking children, that is, in children with very low power-generating abilities, and in the muscle groups that are providing the major contributions to the work of walking. For example, in this laboratory, we have found a situation in which only one muscle group of one leg was providing about 70% of the positive work of walking, and we concluded that surgery on this muscle group would risk making walking impossible. It is likely that work values are closely related to walking velocities, and further research may make it possible to model the predictions of performance with different surgical techniques.

Second, treatment programs must take into consideration the available sources of work during walking. For example, every effort must be made to retain the active range of motion at the ankle in order that the muscular contraction, or moment, can be effective in generating power. In this regard, further work on the effectiveness of casting is warranted. Furthermore, we should train and encourage the active participation during gait of compensatory muscle groups, such as the hip extensors in early stance and the hip flexors at pull-off.

A number of directions of future research are indicated. Of paramount importance is the acquisition of a database for healthy children in order that the data from individual children can be compared. It also appears that the primary deficits of the different types of CP lead to different work compensations, so it is important to report series of subjects who are similar in type and extent of disability. This study is the first of these reports. Further work is needed to determine
the type, nature, and extent of compensations that can be performed with and without interventions. To make predictions about interventions, it will be necessary to relate the work variables to the conditions, to performance variables, and to clinical measures, and then to determine the changes that occur as a result of interventions. Also related to the predictive use of this method, it seems important to establish means of testing the maximum ability to produce work before and after intervention. It is also apparent that much more needs to be known about the work, the compensations, and the interaction of the bursts of work performed by the less-affected limb to provide a complete picture of work and power in the gait of children with CP.

**Conclusion**

This study has documented and quantified the serious deficiencies that exist in the work performed by the ankle plantar flexors of the affected side of hemiplegic children with CP, and these deficiencies are further diminished by concurrent absorption by the knee extensors. Primary, but partial, compensations are provided by the hip extensors during the stance phase and by the hip flexors at pull-off. Without access to such analyses for individual children, we suggest that surgical, orthotic, or physical therapy interventions be undertaken with an awareness of the implications such interventions could have on the power and work capabilities of the child. Furthermore, we believe that the use of information from routine analyses would greatly assist in prescribing and assessing the effectiveness of treatment of children with CP.

**References**


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**Table 2.** Positive and Negative Work per Unit of Body Mass (in Joules per Kilogram) for Children with Cerebral Palsy Compared with Healthy Adults from Winter.

| Joint      | Winter (N = 15) |  |  |  |  |  |  |
|------------|-----------------|----------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|            |                 | X                    | s                 | Range            | X                | s                 | Range            |
| Ankle      | 0.020           | 0.074                | (0.07 to 0.38)    | 0.383            | 0.155            | (0.126 to 0.648)  |
| Knee       | 0.076           | 0.043                | (0.02 to 0.19)    | 0.073            | 0.078            | (0.000 to 0.313)  |
| Hip        | 0.278           | 0.104                | (0.13 to 0.57)    |                  |                  |                  |                  |

**Table 3.** Percentages of Total Positive and Negative Work Attributed to Muscles Across Each Joint for Children with Cerebral Palsy Compared with Healthy Adults at Various Cadences Calculated from Winter.

| Joint      | Winter (N = 15) |  |  |  |  |  |  |
|------------|-----------------|----------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|            |                 | X                    | s                 | Slow             | Natural          | Fast             |
| Ankle      | 0.020           | 0.074                | (0.07 to 0.38)    | 64               | 61               | 57               |
| Knee       | 0.076           | 0.043                | (0.02 to 0.19)    | 10               | 14               | 17               |
| Hip        | 0.278           | 0.104                | (0.13 to 0.57)    | 26               | 25               | 26               |

Note: Slow = mean cadence of 85 steps/min; natural = mean cadence of 105 steps/min; fast = mean cadence of 122 steps/min.
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