Clinical Biomechanics: Contributions to the Medical Treatment of Physical Abnormalities

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Biomechanics is defined as the application of the laws of mechanics to the study or structure and function of movement. It is a relatively new subdiscipline to the domain of kinesiology. Biomechanics was initially closely associated with the study of sports technique. However, over the years, biomechanics has taken on a much more diverse field of study. In this paper, we will describe the contributions that biomechanics has made to the area of clinical biomechanics research in terms of clinical assessment and outcomes and the design of clinical apparatus. The first example examines a clinical assessment of a cerebral palsy child. The goals of such a clinical assessment are 1) to determine the primary problems with the locomotion capabilities of the individual, 2) to recommend treatment options, and 3) to evaluate treatment outcomes. In the second example, a procedure is described for designing braces for scoliosis patients. For this example, a three-dimensional digital twin is developed using a scanning technique. This example illustrates the research conducted on developing a technique to noninvasively and safely determine the torso deformities resulting from scoliosis. While these examples are but two of a wide variety of examples that could be used, they illustrate the contribution of biomechanics to the clinical world.

Biomechanics is defined as the study of the structure and function of animate motion based on the methods employed in mechanics. That is, the kinematics (i.e., the description of motion) and kinetics (the forces involved in causing motion) are used to describe the animate motion. Hatze (1974, page 189) defined biomechanics as “the study of the structure and function of biological systems by means of the methods of mechanics.” There are many definitions of biomechanics but this is the most applicable for this paper. Within the domains of kinesiology, exercise science and/or physical education, the subdiscipline of biomechanics is a relative newcomer. In fact, the first biomechanics laboratories were established in the late 1960s whereas the other exercise sciences such as exercise physiology and motor learning/control/behavior have a much longer history in the kinesiology, exercise science, and physical education domains.

The subdiscipline of biomechanics was initially closely associated with the study of sport techniques. Many of the original studies were descriptions of the techniques employed in sports such as basketball (Yu, Lin, & Garrett, 2006), swimming (McLean, Holthe, Vint, Beckett, & Hinrichs, 2000), gymnastics (Takei, 1989), race-walking (Cairns, Burdett, Pisciotta, & Simon, 1986), and track and field (Hay & Miller, 1985). These studies were essentially a mechanical description of how the athlete preformed skills used in the sport. The titles of these papers reflected descriptive studies and not true experiments. In recent years, the description of motion has been de-emphasized and true experiments with the manipulation of independent variables are more the norm even for studies of sport techniques.

To a great extent, the focus of biomechanical research has changed significantly. Whereas biomechanists initially studied sport techniques, there is a much broader diversity of content in biomechanics research. For example, at the last World Congress of Biomechanics in Singapore in 2010, there were 27 different parallel sessions, each with a different topic area of biomechanics. The topics areas included, for example, such areas as sport technique, musculoskeletal problems, forensic biomechanics, ergonomics, modeling, biomechanics of aging, orthopedics, and reproductive biomechanics, to name a few. One of the major topic areas presented at many biomechanics conferences relates to clinical research. This area focuses on clinical applications of biomechanics in terms of clinical assessment and outcomes, the design of clinical apparatus, modeling of skeletal structures, etc.

The purpose of this paper is to present two examples of biomechanics applied in a clinical setting. First an example will be presented on the biomechanical assessment of a cerebral palsy patient pre- and postsurgery in a pediatric orthopedic hospital. Second, we will describe the research procedures in developing new bracing techniques for scoliosis patients.
Clinical Assessment of a Patient With Cerebral Palsy

Clinical assessments are generally not conducted in biomechanics laboratories in departments of kinesiology/exercise science/physical education. Assessments such as the ones described here typically are confined to gait laboratories in hospitals or clinics. Such an assessment is conducted before surgery to evaluate the current ambulatory status of the patient so that the biomechanist can inform the surgeon of gait impairments that may benefit from correction. The surgeon can then decide on a strategy that may or may not include surgery. If surgery is necessary, then the surgeon can use the assessment to provide an operative strategy. Following the surgery and subsequent recovery from surgery, a postoperative assessment is conducted to determine the success of the procedures. Therefore, the goals of a clinical assessment are 1) to determine the primary problems with the individual’s capabilities, 2) to recommend treatment options, and 3) to evaluate treatment outcomes. Secondary goals include researching the relationships between groups of patients to improve decision-making and educating staff, including medical residents, on the biomechanics of the disability, which in this example is gait.

Gait abnormalities are usually classified at three levels: 1) primary, 2) secondary, and 3) tertiary. Using our present example, the primary abnormality in cerebral palsy (CP) arises from damage to the central nervous system that results in CP. Secondary effects generally result from the primary abnormality, including spasticity, weakness, and joint contracture. Tertiary abnormalities are coping mechanisms to compensate for the primary abnormality. Treatment considerations are based on a three-step process. First is the basic assumption that abnormalities result in increased energy expenditure, increased stress, and decreased function. Medical treatment is currently unable to address the primary lesions that are responsible for CP. The secondary effects are the focus of orthopedic correction and spasticity management. Once correction is made, the tertiary abnormalities (i.e., the compensations) frequently resolve spontaneously.

The process of a clinical assessment involves 1) an observation with video documentation, 2) a clinical examination (usually by a physical therapist), 3) a kinematic and kinetic analysis via a motion capture system and force platform, 4) functional electromyography, 5) a dynamic pedobarographic measure of the plantar surface of the foot, 6) the energy cost of walking, and 7) other outcome instruments such as questionnaires. In many clinical gait laboratories, all patients with cerebral palsy being considered for surgery go through this process. In the example presented here, the patient was a 13-year-old female CP patient who had spastic diplegia and came to the gait laboratory at the Shriners Hospitals for Children in Springfield, MA. She was the product of a 27-week pregnancy. As a result her motor milestones were significantly delayed (e.g., she first ambulated independently at 2 years of age). Before this evaluation, she had surgery at age 4 to 5 years to lengthen the heel-cords of both limbs.

The presurgery kinematics revealed several features that were significantly different from an age-matched typically developing (TD) cohort (Figure 1). There are major differences between the child with CP and the TD cohort at all three joints. In Figure 1, the right side is represented by the solid line and the left by the dashed line. The TD cohort, derived from 50 TD children age 5 to 16, is shown as a hatched region reflecting mean plus or minus one standard deviation. Clinically, the patient is observed to walk with a toe-toe gait pattern, with excessive internal rotation, stiff, flexed knees, and scissoring. These characteristics are well reflected in the kinematics. The sagittal plane ankle angle illustrates that the ankle is always in plantar flexion with no apparent dorsiflexion (equinus gait). The foot progression angle (too-out or toe-in) shows that the patient is always in a toe-in position during the gait cycle, which is contrary to the slightly toe-out position of the TD cohort. The knee flexion/extension angle reveals a markedly reduced range of motion causing the knee to be in a flexed position throughout the cycle. The reduced arc of knee motion in swing phase, specifically, a limitation in peak knee flexion in early swing, and a severe limitation in knee extension in terminal swing are major gait impairments that limit clearance, limb advancement, and step length. Hip flexion shows a generally normal range of motion in flexion and extension with some limited extension in late stance phase that is related to the limited knee extension at that time. At the hip, the abduction/adduction graph shows increased hip adduction throughout stance phase, consistent with a scissoring gait pattern. Hip rotation angles show marked internal rotation averaging nearly 30 degrees on the right, consistent with excessive femoral anteversion. The knee varus/valgus angle shows a grossly normal pattern. The pelvis shows an increased amplitude of sinusoidal excursion in the sagittal plane, reflecting poor dissociation between the pelvis and femur, a classic pattern in spastic diplegia. In the transverse plane, pelvic rotation shows an asymmetric pelvic position with the right side leading the left at all points in the gait cycle, a characteristic that was not recognized during clinical observation.

The most radical differences in the preoperation kinetics between the child with CP and the TD cohort appeared at the knee and ankle (Figure 2). The knee moment for the child with CP demonstrates an increased extensor moment in late stance phase as a result of the increased knee flexion. As a result, the knee power indicates increased energy absorption rather than energy generation at this point in the cycle, showing that the knee extensors are acting eccentrically at this time to produce an antigravity support moment. At the ankle, the moment indicates major differences between the child with CP and the TD cohort during the support period with the child with CP having a much greater plantar flexor moment in the first 50% of stance as a result of toe contact, reflecting
Increased eccentric control by the plantar flexors. During late stance, the plantar flexor moment is reduced and the peak plantar flexor power required for an effective push-off is greatly reduced compared with normal.

Based on these results, the child with CP was deemed to have tight hamstrings, an equinus footfall pattern with tight heelcords, internally rotated hips, tight adductor muscles causing a “scissoring” walking pattern, a compensatory hip circumduction, and significant trunk compensations. The recommendation for alleviating these conditions involved surgery that included: proximal femoral derotation osteotomies, muscle insertion transfers (rectus femoris to sartorius), hamstring muscle lengthening, bilateral Achilles tendon lengthening, and percutaneous adductor muscle releases.

After the surgical interventions, the postoperative kinematics improved significantly at 12 months postoperative (Figure 3). All of pelvic motions were within the ±1 SD bandwidth of the normal cohort as were the hip abduction/adduction and flexion/extension angles. There still appeared to be a problem with hip rotation in which the child with CP was externally rotated while the normal
cohort was in a more neutral position, however, this was an appropriate position to correct the plane of knee flexion/extension and to align the foot progression angle. Knee flexion was greatly improved, with a restoration of full knee extension in midstance phase, reduction of knee flexion at initial contact and in terminal swing. The loading response knee flexion waveform was restored, but is still reduced in amplitude compared with normal. Swing phase range of motion of the knee is greatly improved as a result of the combination of the rectus femoris transfer and hamstring lengthened, which permitted an increased step length. Positive changes were observed in the foot progression angle although there was still a small bilateral difference. The toe-toe gait pattern was converted to a heel-toe pattern, with a normal pattern of flexion extension of the ankle, although because of weakness, the pushoff plantarflexion in late stance is reduced.

Form a kinetic perspective, the hip and knee moment and power were within the normal bandwidth while the ankle moment had the same pattern with lower magnitude values (Figure 4). The major difference between the child with CP and the TD cohort appeared in the plantarflexor power. Rather than a distinct positive power increase at push-off for the TD cohort, the child with CP had a significantly reduced ankle power indicating a much reduced ability to push-off during gait.

The surgery allowed the child with CP to have increased dorsiflexion thereby creating a plantigrade (more heel-toe) footfall pattern. The reduced hamstrings tightness resulted in a less crouched gait and an improved knee range of motion. By increasing the hip abduction range, the child walked with much less scissoring (i.e., limbs crossing over the line of gait). All changes improved the stability of balance during the support period.

Gage (1991) stated that normal gait has several attributes that are frequently lost in pathologic gait and we can compare these with the results pertaining to the child with CP. It appeared that the child had significantly improved stability in stance because she could walk postoperatively with a heel-toe (i.e., plantigrade) rather than an equinus gait. It was also apparent that she had adequate foot clearance during the swing portion of the cycle because she had a substantial knee flexion angle. Her foot was also placed in a more optimum position for the succeeding foot placement in terminal swing phase. Lastly, the heel-toe footfall pattern, as well as complete hip flexion and knee extension allowed the child with CP to achieve an adequate step length. In effect, all of these changes made it possible for the child with CP to walk more efficiently. Qualitatively, the child with CP walked with a more typical gait pattern. Five years postsurgery and with the aid of ankle-foot orthoses, the child continued to walk normally and, most important, more efficiently.

**Clinical Assessment of Scoliosis**

Scoliosis is a three-dimensional spine and trunk deformity that can lead to significant pain and arthritis. The incidence of scoliosis is relatively high with one in every 25 people being affected. Primarily, girls are more affected by this disease than boys. Of those affected by scoliosis, one in every 200 children will require bracing or surgery. Scoliosis is characterized by a lateral spine curvature. The result is a triplanar postural change highlighted by

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**Figure 2** — The preoperative sagittal plane hip, knee, and ankle kinetics of a 13-year-old female with cerebral palsy over a complete gait cycle. The solid (right) and dashed (left) lines represent the time histories of the angles. The hatched area represents ± 1 SD of the typically developing cohort.
Figure 3 — The postoperative three-dimensional hip, knee, and ankle kinematics of a 13-year-old female with cerebral palsy over a complete gait cycle. The solid (right) and dashed (left) lines represent the time histories of the angles. The hatched area represents ± 1 SD of the typically developing cohort.

A lateral trunk offset and rotation, scapular asymmetry and a rib “hump.” It is this latter change that is least understood by the surgeon, most resistant to treatment and most resented by the child. One aspect of scoliosis that is unique is that the physical appearance of the child correlates very highly with psychological distress.

The spine curvature of scoliosis patients is generally evaluated by x-ray. From the two-dimensional x-ray, an angle of curvature referred to as the ‘Cobb Angle’ is developed. Based on the degree of curvature, there are two major treatment protocols for scoliosis. These treatment solutions involve surgery, bracing or a combination of both. The goal of these treatments is to remove or attenuate the lateral spine curvature.

The instrument used at the Shriners Hospital for Children to evaluate spinal curvatures is a 3-dimensional body scanner (Vitus Smart 3D Body Scanner) in conjunction with ScanWorx 3D Scanning Software (Human Solutions, Inc). This scanner consists of 4 lasers and eight cameras that collect over 2 million data points that relate to the surface of the body. From a ‘point cloud’ of data points, a three-dimensional digital twin of the individual
is created. The motivation for the use of such a scanner is twofold: 1) it reduces the radiation exposure of x-rays and 2) it allows for noninvasive diagnosis and monitoring. Therefore, the goal of this research using this scanner is to predict the progression of spinal curvatures and to help develop more effective treatment for scoliosis. Of course, the scanner gives an outline of the outside of the body and not the actual spine.

A method to accomplish the task of representing the torso deformity from the three-dimensional image was developed by a collaboration between researchers at the Shriners Hospital for Children in Springfield, MA and the Department of Kinesiology at University of Massachusetts, Amherst. To do this, a number of “slices” of the three-dimensional representation of the image are taken (Figure 5). To analyze a scan, first an ellipse was fit to the point cloud for a reference slice defined at the level of the posterior superior iliac spines. The center of this ellipse and orientation of its principal axis served as reference for all measurements. The upper extent of useful data was identified based on a clear definition between the torso and arms in the upper thoracic region. The software then fit an ellipse to the point cloud for each slice within the defined volume. Finally, the software determined the fore/aft and medial/lateral deviation (in mm) of the origin of each ellipse as well as the orientation (in degrees) of the principal axis of each ellipse relative to the pelvic reference. The goodness of fit of each ellipse to its underlying point cloud was quantified as the root mean square deviation of the points to the ellipse. Right/left symmetry of each scan slice was determined by comparing the area encompassed by the right and left halves of the point cloud divided along the minor axis of the ellipse. The maximum deviation from the pelvic reference in each direction (fore/aft, medial/lateral, clockwise/counterclockwise, right/left) of any slice within the defined volume was recorded as well as the range.

This method of three-dimensional body scanning has a singular advantage. That is, it allows for spinal deformities to be classified mathematically. Therefore, the change in shape pre- and postsurgery or pre- and postbracing, for example, can be quantified and the progression of the scoliosis curve can be monitored. In addition, it may be possible to use a regression equation to predict the progression of the curve.

The information gained from the scanner technique can be used in a number of ways both from a research and clinical perspective. From the research perspective, the digital image may be used to develop new bracing techniques or to evaluate the spinal deformity correction afforded by different surgical instrumentation strategies. On the other hand, clinically it may be used to determine the progression of the disease of a single individual.

**Biomechanics and Clinical Assessment**

Using biomechanics in clinical assessment can be very useful to determine the primary levels of abnormalities and possibly create a situation in which an attempt to rectify the consequences of the abnormalities can be made. However, it should be noted that the outcomes of surgical interventions such as those described for cerebral palsy...
or scoliosis may not be 100% successful in terms of the treatment aims but may be only moderately successful. Biomechanical assessment aids the physician in knowing whether the treatment has met the aims set at the preoperative evaluation.

Summary

The discipline of biomechanics is new to the field of kinesiology/exercise science/physical education and has developed over the years as more than simply a set of measurement tools to describe human motion. While biomechanics began as a study of sport technique, the field has developed many widely different areas of study that employ the various measurement tools of mechanics. One of these areas in which biomechanics has contributed significantly to society is clinical biomechanics. This area alone has developed a considerable array of both practical and experimental procedures that have helped clinicians. In this paper, we described an example of a child with CP who benefitted from a practical application of biomechanics to the analysis of her locomotor patterns. From this analysis, a treatment protocol was established to correct her gait to make it more economical. The second example illustrated the research conducted on developing a technique to noninvasively and safely determine the torso deformities resulting from scoliosis.

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References


