International Journal of Paediatric Orthopaedics | January-April 2024; 10(1): Page 09-13

Symposium

POSI
IJPO

Understanding the Biomechanics of Lever Arm Disorders in Cerebral Palsy

Jayanth Sampath MS Ortho[1], Taral Nagda MS Ortho[2]


Dr. Jayanth Sampath


Dr. Taral Nagda

Abstract

Levers in the human body play an important role in facilitating efficient movement. Muscle forces act around the axis of movement of adjacent joints. The normal moment of a joint (M) is the product of the muscle force (F) and the length of lever arm (d). The primary neurological insult in cerebral palsy (CP) causes shortening of muscles, joint contractures, and torsional abnormalities in bones. The resulting ineffective lever arm leads to a failure to produce an appropriate torque and subsequent gait abnormalities. Therefore, the effects of lever arm dysfunction should be considered when gait improvement surgery is being offered to children with CP. This review will explain the role of levers in normal human biomechanics and the significance of lever arm dysfunction in the management of CP.

Keywords: Biomechanics, Lever arm, Disorder, Cerebral palsy

Introduction

Cerebral palsy is primarily a neurological disorder affecting movement and posture. Skeletal muscles in children with CP appear to have a fundamental inability to lengthen in response to longitudinal growth of the appendicular skeleton. This produces relative shortening of muscle in relation to bone length (muscle contracture) leading to joint contractures and bony deformity.

Dr James Gage and colleagues coined the term "lever arm dysfunction" to describe abnormalities in the bones and joints of the lower extremities resulting in altered gait in cerebral palsy. In simple terms, the presence of skeletal deformity results in decreased efficiency, requiring more work and effort for the muscles to provide the propulsion energy to move the body forward during gait.

Musculoskeletal consequences of cerebral palsy

Skeletal:

The positive features of the upper motor neuron (UMN) disorder (spasticity, hypertonia, clonus, and co-contraction) cause dynamic muscle contractures in CP. This, along with the negative features of the UMN syndrome namely muscle weakness, impaired selective motor control, poor coordination, poor balance), reduce physiological muscle stretching, which is essential for the normal muscle growth. Impaired muscle stretching in turn results in changes in the intrinsic mechanical structure of spastic muscles. Spastic muscles become inelastic, thinner, and shorter with longer tendons giving rise to fixed contractures.

When fixed contractures are not treated early, the growing skeleton is subjected to uneven forces. This progressively leads to a change of the bone shape and, finally, to musculoskeletal deformities. The musculoskeletal deformities cause disturbance of the internal and external lever-arms giving rise to lever arm dysfunction. The result is a significant reduction in the mechanical advantage of muscles thereby impairing ambulatory function.

Thus, the motor deficits in cerebral palsy pass through three stages

a. Primary impairment: Spastic muscles are not able to stretch and cause unequal

Address of Correspondence
Dr. Jayanth S. Sampath,
Rainbow Children's Hospital, Bangalore, Karnataka,
India.
E-mail: jayanthdoc@gmail.com

[1]Department of Paediatric Orthopaedics, Rainbow Children's Hospital, Bangalore, Karnataka, India.
[2]Department of Paediatric Orthopaedics, SRCC NH Children's Hospital, Mumbai, Maharashtra, India.

DOI- https://doi.org/10.13107/ijpo.2024.v10i01.172
www.ijpoonline.com

Submitted: 01/02/2024; Reviewed: 14/02/2024; Accepted: 18/03/2024; Published: 10/04/2024

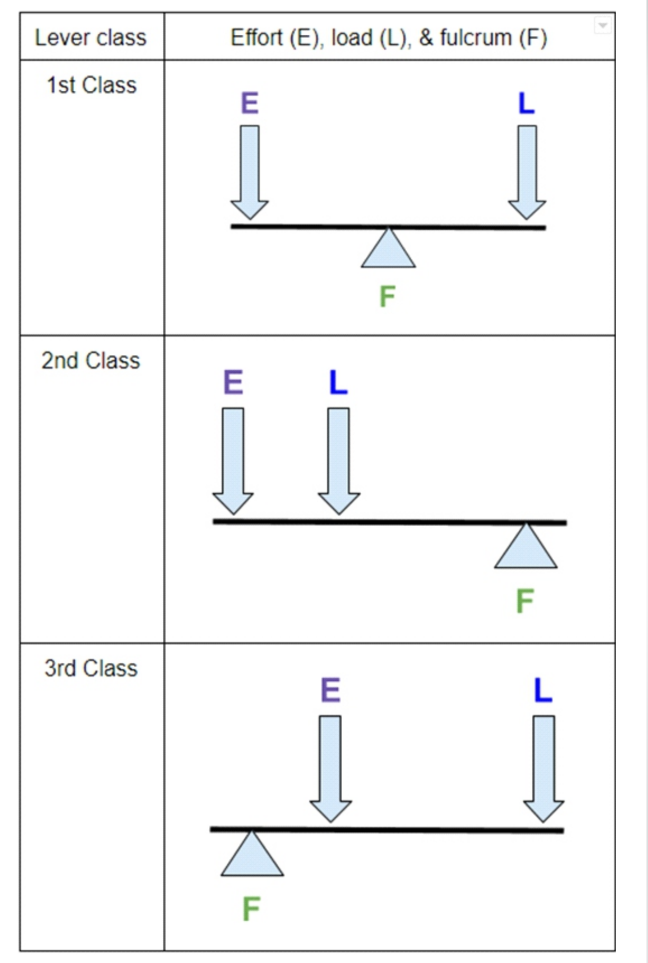

Figure 1: is a diagrammatic representation of the three classes of levers.

muscle forces leading to dynamic joint deformities.

b. Secondary impairment: The muscles under tension cannot grow as well as normal muscles. This causes relative shortening of muscles and fixed contractures of muscles.

c. Tertiary impairment: As the child's age advances, there are secondary contractures in the adjacent joints and rotational deformities in bones which cause lever arm dysfunction.

These impairments may coexist in a child. Careful assessment of the child is paramount to differentiate between primary, secondary, and tertiary level impairments.

What is a lever?

The principles of levers were developed by Archimedes 260 B.C. A lever is a rigid body rotating about an axis called the pivot. In the human body, bones could be considered as the rigid body segments rotating around a joint as the pivot with forces created by the adjoining muscles and ligaments. In the human body, joints act as the pivot or fulcrum (F), muscles provide the effort (E) whereas a combination of inertial resistance and weight of the body part provides the load (L).

The Three Types of Levers

There are three different kinds of levers: first class, second class, and third class (or) class 1, 2 and 3 respectively. Each of these classes of lever have different configurations of effort and load around the joint (Fig. 1). In a first-class lever, the fulcrum is present between the effort and the load. In a second-class lever, the load is situated between the fulcrum and effort and in a third-class lever, the effort is located between the fulcrum and the load.

Examples of levers in human body

All the classes of levers are present in the human body; however, class three is the most common. The first class of lever has the fulcrum (pivot) situated between the body segment weight (resistance) and muscular force (e.g. movement around the atlanto-occipital joint). The second class of lever could be seen as weight applied to the toes where resistance falls between the axis and force. There are many examples of third class of lever where this axis lies in between the resistance and the force (e.g. knee joint movement).

Efficiency of levers (Effort Arm vs. Load Arm)

The efficiency of a lever is dependent on the ratio of the effort arm to the load arm. This is termed "mechanical advantage" (MA). It can be expressed as MA = Effort arm/ Load arm where MA = mechanical advantage, Effort arm = Distance from effort to fulcrum and Load arm = Distance from load to fulcrum (Fig. 2).

If the effort arm is greater than the load arm, then mechanical advantage is greater than one. Therefore, the greater the distance between the effort and fulcrum, the easier it is to displace the load since a smaller effort is necessary. In other words, situating the fulcrum close to the load is useful in minimizing the effort.

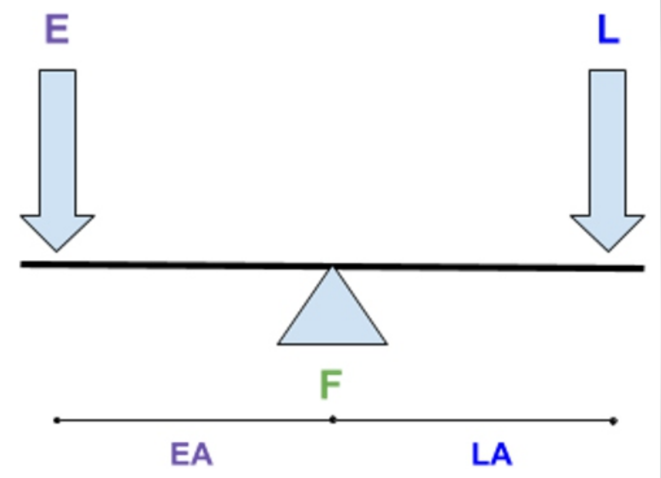

Figure 2:showing the effort arm and load arm on either side of the fulcrum. Changes to the relative lengths of the effort and load arms alters the mechanical advantage of the lever. (EA: Effort arm, LA: Load arm.)

The effort arm (EA) is the distance between the fulcrum and the effort; in the human body, this is the distance between a joint centre and the site of insertion of the concerned muscle. The load arm (LA) is the distance between the fulcrum and the load; i.e. the distance between the joint centre and the body part distal to the joint (load).

The greater the ratio of the effort arm to the load arm, the more efficient the lever system is (i.e. the less the effort to displace the load). Therefore, if the distance between a muscle's insertion site and the joint is greater than the distance between the load and the joint, your muscle is at an advantage.

Velocity Ratio

Velocity ratio is the ratio of distance travelled by the load to that travelled by the effort.

The longer the effort arm, the easier it is to move the load but less is the distance travelled by the load. The shorter the effort arm, a larger force is required to move the load but the distance travelled by the load is increased, thereby acting as a speed multiplier.

For a class II lever, EA is always greater than LA (See Fig. 1) This results in a mechanical advantage that is greater than 1, and the lever acts as a force multiplier.

For a class III lever, EA < LA; the mechanical advantage is always less than 1 and the lever always acts as a speed multiplier.

For a class I lever, EA and LA can take every possible value greater than 0 (bounded by the length of the lever, of course). According to the ratio of LA and EA, such a lever can be a force multiplier or a speed multiplier. If EA > LA, a class 1 lever will be a force multiplier and if EA < LA, the class 1 lever will be a speed multiplier.

The hip as a First-Class lever

In the case of the hip as a class 1 lever, the center of the femoral head is the fulcrum (F) with the body weight acting as the load (L) and the abductor muscles providing the effort arm (E) (Fig. 3). F is in the center with the effort and load arms on either side. The distance from the hip joint centre to the attachment of the hip abductors is the effort arm (EA). The distance from the hip centre to the centre of gravity of the human body provides the load arm (LA). The efficiency of this lever depends on the length of the effort arm. The greater the length EA, the easier it is for the abductors to counteract the moment due to gravity and maintain a level pelvis. Failure of this lever mechanism manifesting as Trendelenburg gait can occur because of:

1. Abnormal or displaced fulcrum: Lateral displacement of the hip in cerebral palsy
2. Shortened effort arm: Coxa valga and breva
3. Inefficient lever arm: Fracture neck of femur
4. Inadequate effort force: Abductor weakness or laxity due to a high riding trochanter

The foot as a Second-Class Lever

In plantar flexion, the lower leg acts as a class 2 lever. During calf raise, the fulcrum is situated at the metacarpophalangeal joint, the gastric-soleus muscle complex attached to the calcaneum provides the effort and the load is the body weight acting through the tibia (Fig. 4).

A second-class lever is termed a "Power Lever" or force multiplier and the only situation where the effort arm is greater than the load arm. This arrangement results in a higher effort arm to load arm ratio. The load is in the middle and the effort farthest from the fulcrum making the second class lever the most mechanically advantageous. Therefore, the act of plantarflexion can displace much greater weights than elbow flexion, even if the biceps is just as strong as the calf muscle group.

The knee joint as a Third-Class lever

During extension of the knee, the knee joint centre acts as the fulcrum, with the weight of the leg acting as the load and the quadriceps muscle group providing the effort. In this case, the effort arm lies between the fulcrum and load arms. Since the effort arm is shorter, the lever system is at a relative mechanical disadvantage. However, there is greater excursion of the load with lesser excursion of the effort resulting in a better arc of movement (speed multiplier).

Why are levers important in cerebral palsy

Lever arm dysfunction in children with cerebral palsy refers to the inefficiency of gait resulting from a combination of abnormal skeletal development, joint contractures, and foot deformity.

In the human body, the centres of rotation of joints act as the axis about which muscle forces are applied. A force that acts about an axis is called a moment (M), equal to the muscle force (F) times its perpendicular distance (d) from the axis of joint rotation. $M = F \times d$. If one remembers that a muscle always acts as part of a force-couple or moment (M), it should be apparent that an inadequate moment arm (lever or 'd') will produce apparent weakness even in the face of adequate muscle force (F). Coxa valga is a typical example where the abductor lever arm in the coronal plane is reduced causing an abductor lurch even when the abductors are of sufficient strength.

In cerebral palsy, lower limb levers at hip knee and ankle are also altered. Lever arm dysfunction typically progresses with growth in children with CP resulting in greater gait deviations over time.

While considering the management of musculo-skeletal deformity, optimal treatment of the lever arm significantly improves the quality of movement in children with CP.

Types of lever arm disorders in CP

There are different types of lever arm dysfunctions in cerebral palsy. One must bear in mind that in each clinical situation, several types of lever arm problems can coexist with different lever arm problems at different joints and a combination of lever arm issues at one joint. Thorough knowledge of the various types of level arm dysfunction and their impact on gait is therefore essential for the proper management of gait impairments in cerebral palsy.

1.Short lever arm (coxa valga)
2. Flexible lever arm (pes valgus)
3, Malrotated lever arm (external tibial torsion)
4. Abnormal pivot (hip subluxation or dislocation)
5. Positional lever arm dysfunction (crouch gait)

Effect of Lever arm disorder in CP

The effects produced by lever arm disorders are of two types

1. Change the line of muscle action, line of gravity and ground reaction force resulting in abnormal internal and external joint moments.
2. Change in the mechanical advantage (MA) of the body system. MA is based on the ratio obtained from internal and external moment arm that affects body joint and its function.

A detailed description of the causes, effects, and management of lever arm dysfunction at the hip, knee, and foot levels are provided in later articles in this IJPO symposium on cerebral palsy.

Conclusion

Children with CP exhibit a variety of lever arm disorders with characteristics changes in gait pattern. The surgical approach for gait correction depends predominantly on an assessment of the child's gait through 2-D videos or instrumented gait analysis. An understanding of lever arm dysfunction is important to achieve appropriate surgical correction. Various surgical procedures have been used for the correction of ankle, knee, and hip lever arm dysfunction. The choice of the surgery and its outcome is suited best with kinetics and kinematics analysis of gait.

References

1. Gage JR, editor. The treatment of gait problems in cerebral palsy. 2nd ed. London: Mac Keith Press; 2004. Treatment principles for crouch gait; p 382-97.

2. Theologis T. Lever arm dysfunction in cerebral palsy gait. J Child Orthop. 2013;7(5):379-382.

3. Kalkman BM, Bar-On L, Cenni F, et al. Achilles tendon moment arm length is smaller in children with cerebral palsy than in typically developing children. J Biomech. 2017;56:48-54.

4. Õunpuu S, Solomito M, Bell K, Pierz K. Long-term outcomes of external femoral derotation osteotomies in children with cerebral palsy. Gait Posture. 2017;56(March 2016):82-88..

5. Kim HY, Cha YH, Chun YS, Shin HS. Correlation of the torsion values measured by rotational profile, kinematics, and CT study in CP patients. Gait Posture. 2017;57:241-245.

6. Saglam Y, Ekin Akalan N, Temelli Y, Kuchimov S. Femoral derotation osteotomy with multi-level soft tissue procedures in children with cerebral palsy: Does it improve gait quality? J Child Orthop. 2016;10(1):41-48.

7. Kadhim M, Miller F. Crouch gait changes after planovalgus foot deformity correction in ambulatory children with cerebral palsy. Gait Posture. 2014;39(2):793-798.

8. Kadhim M, Holmes L, Miller F. Long-term Outcome of Planovalgus Foot Surgical Correction in Children with Cerebral Palsy. J Foot Ankle Surg. 2013;52(6):697-703.

9. Kim HT, Jang JH, Ahn JM, Lee JS, Kang DJ. Early results of one-stage correction for hip instability in cerebral palsy. Clin Orthop Surg. 2012;4(2):139-148.

10. Ganjwala D. Multilevel orthopedic surgery for crouch gait in cerebral palsy: An evaluation using functional mobility and energy cost. Indian J Orthop. 2011;45(4):314..

11. Foroohar A, McCarthy JJ, Yucha D, Clarke S, Brey J. Head-shaft angle measurement in children with cerebral palsy. J Pediatr Orthop. 2009;29(3):248-250.

12. Rethlefsen SA. Causes of Intoeing Gait in Children with Cerebral Palsy. J Bone Jt Surg. 2006;88(10):2175..

13. Čobeljić G, Djorić I, Bajin Z, Despot B. Femoral derotation osteotomy in cerebral palsy: Precise determination by tables. Clin Orthop Relat Res. 2006;(452):216-224.

14. Kadhim M, Holmes L, Church C, Henley J, Miller F. Pes planovalgus deformity surgical correction in ambulatory children with cerebral palsy. J Child Orthop. 2012;6(3):217-227.

15. Aiona M, Calligeros K, Pierce R. Coronal plane knee moments improve after correcting external tibial torsion in patients with cerebral palsy. Clin Orthop Relat Res. 2012;470(5):1327-1333.

16. Davids JR, Gibson TW, Pugh LI, Hardin JW. Proximal femoral geometry before and after varus rotational osteotomy in children with cerebral palsy and neuromuscular hip dysplasia. J Pediatr Orthop. 2013;33(2):182-189.

17. Rodda JM, Sciences H. Severe Crouch Gait in the Sagittal Gait Patterns of Spastic Diplegic Cerebral Palsy : the Impact of Single Event Multilevel Surgery. 2005;(November).

18. Inan M, Altinta?? F, Duru I. The evaluation and management of rotational deformity in cerebral palsy. Acta Orthop Traumatol Turc. 2009;43(2):106-112.

19. Heimkes B, Stotz S, Heid T. Pathogenesis and prevention of spastic hip dislocation. Z Orthop Ihre Grenzgeb. 1992;130(5):413-418.

20. Pirpiris M, Trivett A, Baker R, Rodda J, Nattrass GR, Graham HK. Femoral derotation osteotomy in spastic diplegia. J Bone Jt Surg.

2003;85(2):265-272.

21. Noonan K, Halliday S, Browne B, et al. Interobserver variability of gait analysis in patients with cerebral palsy. J Pediatr Orthop 2003; 23:279 – 287.

22. States RA, Krzak JJ, Salem Y, Godwin EM, Bodkin AW, McMulkin ML. Instrumented gait analysis for management of gait disorders in children with cerebral palsy: A scoping review. Gait Posture. 2021 Oct;90:1-8. doi: 10.1016/j.gaitpost.2021.07.009. Epub 2021 Aug 3. PMID: 34358847.

23. Wren TA, Gorton GE 3rd, Ounpuu S, Tucker CA. Efficacy of clinical gait analysis: A systematic review. Gait Posture. 2011 Jun;34(2):149-53. doi: 10.1016/j.gaitpost.2011.03.027. Epub 2011 Jun 8. PMID: 21646022.

24. Narayanan UG. The role of gait analysis in the orthopaedic management of ambulatory cerebral palsy. Curr Opin Pediatr. 2007 Feb;19(1):38-43. doi: 10.1097/MOP.0b013e3280118a6d. PMID: 17224660.

Declaration of patient consent : The authors certify that they have obtained all appropriate patient consent forms. In the form, the patient has given the consent for his/ her images and other clinical information to be reported in the journal. The patient understands that his/ her names and initials will not be published and due efforts will be made to conceal their identity, but anonymity cannot be guaranteed.

Conflict of interest: Nil **Source of support:** None

How to Cite this Article

Sampath J, Nagda T | Understanding the Biomechanics of Lever Arm Disorders in Cerebral Palsy | International Journal of Paediatric Orthopaedics | January-April 2024; 10(1): 09-13 .