Review Article

FORCE COUPLE MECHANICS ON FEMUR DURING CLOSED KINETIC CHAIN ACTIVITIES OF LOWER LIMBS

R.Vinodh Rajkumar.

Founder: PALEOLITHICX, Physiotherapist & Functional Fitness Training Instructor (Freelance), Bangalore, Karnataka, India.

ABSTRACT

Exploration of the biomechanical interaction of musculoskeletal system keeps endorsing the fact that the human body can ensure efficient biomechanics without any kinematic aberrations in the joints. Excluding the injuries caused by unexpected collisions, the major potential factors that ruin the protective configuration of musculoskeletal system can be lack of exercise and incorrect exercise. A fresh perspective; 'force couple mechanics (FCM) on femur' (torque on femur by two muscular forces in opposite directions at two different locations), has been discussed in this article using fundamental information on anatomical linkages of muscles & correlation of various scientific reports, finally expected to stimulate electromyographic studies to dig out further scientific data.

KEYWORDS: Force couple mechanics on femur, Gluteus maximus, Vasti.

Address for correspondence: R. Vinodh Rajkumar, # 638, 1st Floor, Jakkuramma Building, Behind Eswara Temple, 1st Cross, 1st Main, Mathikere, Bangalore-560054, Karnataka, India.
Mobile: 9008424632. **E-Mail:** dreamofkalam@rediffmail.com

INTRODUCTION

Exploration of the biomechanical interaction of musculoskeletal system keeps endorsing the fact that the human body can ensure efficient biomechanics without any kinematic aberrations in the joints. Excluding the injuries caused by unexpected collisions, the major potential factors that ruin the protective configuration of musculoskeletal system can be lack of exercise and incorrect exercise. A fresh perspective; 'force couple mechanics (FCM) on femur' (torque on femur by two muscular forces in opposite directions at two different locations), has been discussed in this article using fundamental information on anatomical linkages of muscles & correlation of various scientific reports, finally expected to stimulate electromyographic studies to dig out further scientific data.

Biomechanical analysis

To understand the role of FCM on femur, the fundamental of closed kinetic chain angular motion has to be understood as follows; "If a push force is applied on a stable surface through one terminal part of a rigid lever (point-A), then the other terminal part (B) will tend to move away from its original position using point-A as axis to result in angular displacement (ø) of the entire lever, but to get this type of mechanical interaction during closed kinetic chain circumstances in human body, a force couple system (F1, F2) must act on that lever" - Figure 1a, 1b.

The stability of the lever at point-A is very crucial if the goal of the FCM is to lift point-B upwardly without any scope for it to get displaced in any unintended direction. At the

same time, the direction of application of F1 & F2 is also important to get this rotational effect on the lever. For instance, if the F1 & F2 are applied on the lever as shown in Figure-1c, then the mechanical outcome will be entirely different in which point A will tend to move away from the stable surface.

Fig. 1: Fundamental of closed kinetic chain angular motion.
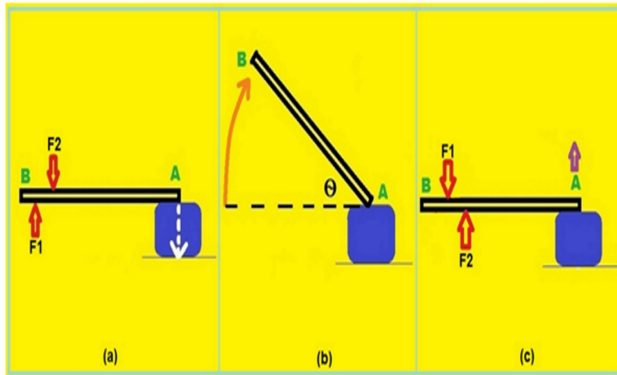
The femur, being a rigid skeletal lever, also tends to move similarly in the sagittal plane during various closed kinetic chain (CKC) movements of lower extremities. In this article, squat has been chiefly considered for a sagittal plane analysis to interpret the probable force couple muscular system and other supportive biomechanics essential for effective FCM on femur during CKC activities of lower extremities. As a result of force couple mechanics at the proximal part of femur, the femoral condyles must apply compressive force on the stable tibial plateau (Figure-2a) resulting in upward angular displacement (ø) of the femur (Figure-2b). It is easy to identify the muscular system involved in FCM on femur because for sure the point of application of force that pulls the femur downward should be located distal to the point of application of force that pulls the femur upward. From anatomical view point, Gluteus maximus can apply the downward force at gluteal tuberosity located distal to the origin of Vasti group (Vastus lateralis, Vastus medialis & Vastus intermedius) of Quadriceps which can exert the upward force (Figure-2c). Caterisano et al indicated the increasing activity of Gluteus Maximus (GM) as the squat depth increases.[1] Escamilla et al found that the EMG activity of Vasti (V) was greater than Rectus femoris and the muscular force output of Vasti was 50% greater than that of Rectus femoris.[2]

When F1 and F2 are acting as force couples on a rigid skeletal lever in the body, particularly if any heavy load is placed at or near the movable end of the lever, the F1 (component that is closer to the movable end) can act like a fulcrum. The function of Vasti in FCM on femur can be interpreted as a fulcrum whilst the role of GM is to counterbalance the torque caused by mass of Head, Arms and Trunk (mass of HAT) placed on the femoral head to ultimately execute control over the angular displacement of femur during ascent and descent of squat (Figure-3a, 3b). The work load for Vasti and Gluteus maximus during squat is quite larger because the percentage contribution of the mass of HAT to the total body mass of an individual itself, based on the studies of body segment parameters of de Leva and Plagenhoef et al, can be up to 59.26 % and 73.12%, respectively.[3,4] However Pearsall et al did a review on studies about body segment parameters and suggested that the future efforts in this context should be directed towards addressing its various weaknesses, in order to improve biomechanical investigation in the clinical, ergonomic and sport environments.[5]

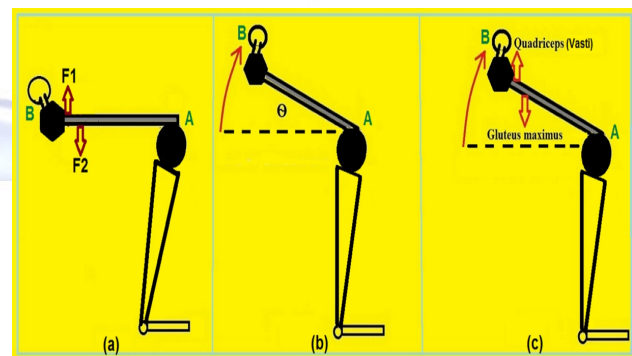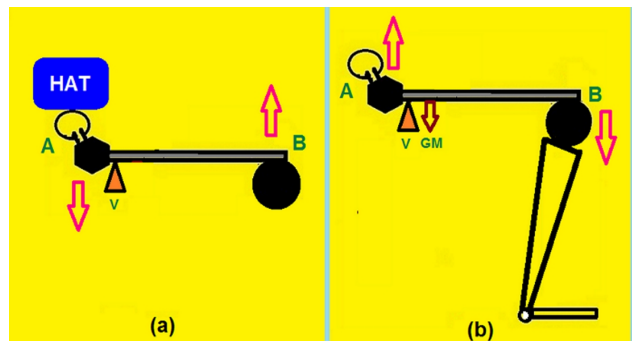**Fig. 2:** Force couple mechanics on femur.

Fig. 3: Interaction of HAT, Vasti and Gluteus maximus.

By acting like a fulcrum, the Vasti can form a first class lever system with much lesser resistance arm (RA) for Gluteus maximus (Figure-4b) as compared to the resistance arm of

Vasti (Figure-4a). To effectively maneuver this force couple mechanics on femur, two major supportive biomechanics may be required (i) Strong working foundation for Gluteus maximus and Vasti (ii) Stable axis at knee joint.

Gluteus maximus must apply strong forces on gluteal tuberosity of femur without causing a posterior pelvic tilt, so its proximal attachment site must be stabilized. Iliopsoas can help in creating a working foundation as they can act as an antagonist to the gluteal muscles to control posterior pelvic tilt during squat.[6] Generally the pelvic stability and its alignment in the sagittal plane can also be expected through co-contraction of Rectus femoris and Hamstrings. In sagittal plane, the anatomical linkage of Rectus femoris and Hamstrings on pelvis and knee simulates the inter-dependent activities of dissimilar sized pulleys used in machines (Figure-5). Through such arrangement, Rectus femoris and Hamstrings muscular system can constantly have direct reciprocal control on pelvic alignment in the sagittal plane which in turn induces necessary changes in the trunk muscle recruitment to stabilize the vertebral column. During Gluteus maximus contraction in this CKC circumstance, the pelvis can be prevented from tilting posteriorly if the activity of Rectus femoris remains greater than the Hamstrings. The role of Rectus femoris may be crucial during the disruption of upright standing posture to initiate squat and that can be correlated with decreased activities of Hamstrings during initiation of squat as reported by Cheron et al whilst the concomitant role of Tibialis anterior in initiating squat was recognized by Cheron et al & Valdeci et al.[7,8] Hence, Iliopsoas and Rectus femoris can prevent posterior tilting of pelvis and provide a strong working foundation for Gluteus maximus to act on femur.

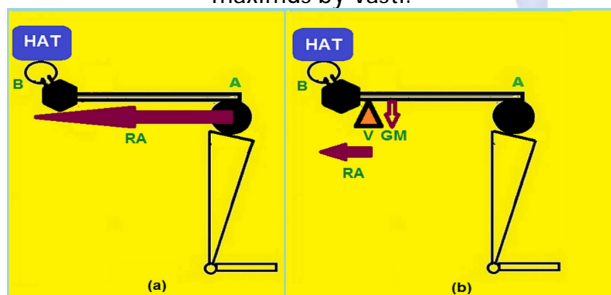**Fig. 4:** Formation of first class lever system for Gluteus maximus by Vasti.

Fig. 5: Sagittal view of arrangement of Rectus femoris and Hamstrings resembling interaction of mechanical pulleys. HJ - Hip joint, KJ - Knee joint, AJ- Ankle joint, PF - Plantar flexors, DF - Dorsiflexors, P - Pelivs, Q - Quadriceps, H - Hamstrings, R – Ribcage
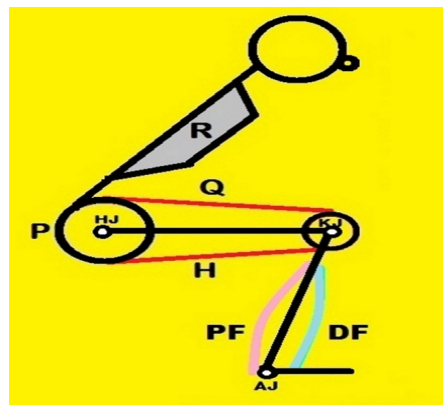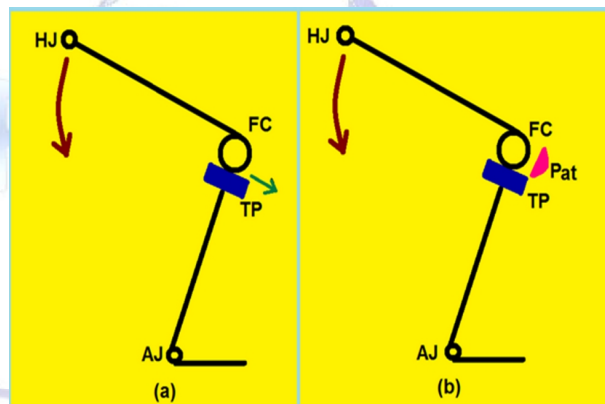

Fig. 6: Possible advantage of anterior inclination of tibial plateau and presence of patella. HJ - Hip joint, AJ - Ankle joint, TP - Tibial plateau, FC - Femoral condyle, Pat – Patella.

On the other hand, the Vasti muscles must apply strong forces on inter-trochanteric region of femur with its distal attachment site stabilized to prevent unwanted knee extension thrust (similar to knee extension in open kinetic chain) and disturbances in the knee joint axis caused by anterior translation effects on tibia. The knee extension thrust caused by Quadriceps gets easily neutralized by CKC ankle dorsiflexion and transmission of sufficient load through the lower extremities resulting in increased friction at the interface between feet and floor. At the same time, the tendency of Quadriceps to produce anterior translation effects on tibia can get offset by Hamstrings as it is believed to exert a counter-regulatory pull on the tibia to alleviate stress on the anterior cruciate ligament. [9,10]

Stable axis at knee joint is very crucial for effective FCM on femur although the sagittal plane orientation of the tibial plateau (TP) will

be under the control of dorsiflexors and plantar flexors. CKC dorsiflexion of ankle displaces the knee joints downwardly and forwardly producing anterior inclination of tibial plateau whilst the CKC plantarflexion of ankle displaces the knee joints upwardly and backwardly with the tendency to restore the horizontal orientation of tibial plateau. Various supportive mechanisms can be facilitating perfect spinning of femoral condyles on the tibial plateau, not only in favor of protecting the knee from injuries but also in favor of this force couple mechanics on femur.

Apart from executing postural control, the CKC ankle dorsiflexion during squat may possess multiple biomechanical advantages by tilting the tibia and tibial plateau anteriorly. Anterior inclination of tibial plateau can also facilitate the required anterior gliding of femoral condyle to reduce the stress in anterior cruciate ligament (ACL) during initial stages of flexion of knee in CKC. Hamstrings activity has been linked with reducing stress on ACL and its peak activity was found to occur anywhere between 10° and 70° of knee flexion.[11] So, the anterior inclination of tibial plateau and Hamstrings activity may together play a vital role to safeguard ACL, especially when the Quadriceps activity tends to peak. Peak activity of Quadriceps has been noted at approximately 80° to 90° of knee flexion.[9] Any excess anterior gliding of femoral condyle can also be retarded by patella to prevent elevation of the stress in posterior cruciate ligament (PCL) or by PCL to prevent elevation of patellofemoral joint reaction forces (Figure 6a,6b). Shields et al studying the co-contraction between the Quadriceps and the Hamstrings in the squat exercise in three load levels have verified that the activity of the Quadriceps muscle was higher than the Hamstrings for all levels.[12] PCL forces, which were generated throughout the squat descent and ascent, progressively increased as the knees flexed and decreased as the knees extended.[13]

Controlled dorsiflexion caused by Soleus can be another supportive system to neutralize the anterior tibial translation effects of Quadriceps. The Soleus muscle slows down the ankle dorsiflexion and creates a knee extension torque, forcing the tibia backwards, which minimizes the anterior shear force in the knee joint.[14] Posterior tibiofemoral shear force on ACL-intact knees indicated that the potential loading on the injured or reconstructed anterior cruciate ligament is not significant and also the magnitude of the posterior tibiofemoral shear force is not likely to be detrimental to the injured or reconstructed posterior cruciate ligament.[15]

Deep squats and activities with deep knee flexions (Photograph - 1 & 2) could demand greater magnitude of angular displacement of femur and the total work output from FCM on femur. Knee structures are highly constrained at angles greater than 120°, resulting in much less anterior and posterior tibial translation and tibial rotation in comparison with lesser flexion angles.[16] Dislocating effect on the knee caused by compression of posterior thigh and calf muscles has been one of the concerns of deep squat according to Kreighbaum et al.[17] In deep knee flexion angles, the ACL and PCL can almost get aligned horizontally and vertically respectively, through which the dislocating effects on the knee caused by compression of posterior thigh and calf muscles may get prevented. However, failure to control the squat descent can result in the ballistic contact between the hamstrings and calf muscles, which can cause a dislocating effect on the knee ligaments.[18] Hence when all such protective mechanisms work in perfect balance, the axis at knee joint can remain stable to effectively support the FCM on femur.

Photograph 1: Deep squat. **Photograph 2:** Climbing up high platform.

The major biomechanical challenge during CKC activities of lower extremities is to move the trunk in the purposeful directions often associated with purposeful activities of upper

extremities, for which spinal stability is vital. Stability of spine is determined by activation levels of all trunk muscles, regardless of the magnitude of Intra-abdominal pressure (IAP) and the effectiveness of IAP becomes most effective at stabilizing the spine when applied in concert with co-activation of the Erector spinae muscles.[19] Any increased hoop tension created by the Transversus abdominus and Internal oblique abdominal muscles would serve to not only increase IAP, but it would also increase segmental joint stiffness and serve to stabilize the spine in all planes of motion.[20] But the recruitment of trunk muscles may depend on the mechanisms that ensure stability of pelvis and knee joint to support the FCM on femur. For example, the abdominal muscles should enhance the stability of lumbar spine while Iliopsoas contracts to provide working foundation for Gluteus maximus during FCM on femur.

CONCLUSION

From biomechanical perspective, a wide range of CKC activities of lower extremities that incorporates knee flexion and ankle dorsiflexion, irrespective of the magnitude of range of motion, may be inevitably relying on this force couple muscular system on femur, however electromyographic studies on the basis of this concept is warranted to dig out relevant scientific data. This concept of FCM on femur and its related supportive biomechanics can also be part of the future research efforts in the field of Physical therapy rehabilitation and fitness training to further enhance the understanding of biomechanics of CKC activities like stair climbing, squats, lunges, bent-knee dead lifts, jumps and all other locomotion.

Conflicts of interest: None

REFERENCES

1. Caterisano A, Moss RF, Pellinger TK, Woodruff K, Lewis VC, Booth W, Khadra T. The effect of back squat depth on the EMG activity of 4 superficial hip and thigh muscles. J Strength Cond Res. Aug 2002; 16(3): 428-32.
2. Escamilla RF, Fleisig GS, Zheng N, Barrentine SW, Wilk KE, Andrews JR, Biomechanics of the knee during closed kinetic and open kinetic chain exercises. Med Sci Sport Exerc. 1998;30:556-69.
3. De Leva P, Adjustments to Zatsiorsky-Seluyanov's Segment Inertia Parameters, Journal of Biomechanics 1996;29(9):1223-1230.
4. Plagenhoef S, Evans F.G, Abdelnour T. Anatomical data for analyzing human motion. Research Quarterly for Exercise and Sport 1983;54;169-178.
5. Pearsall DJ, Reid JG, The study of human body segment parameters in biomechanics. An historical review and current status report, Sports Med. 1994 Aug;18(2):126-40.
6. Mike Decker, Jake Krong, Dan Peterson, Tyler Anstett, Michael Torry, Erik Giphart, Kevin Shelburne,Marc Philippon, Deep hip muscle activation during a squat exercise. Retrieved from http://www.asbweb.org/conferences/2009/943.pdf
7. Cheron G, Bengoetxea A, Pozzo T, Bourgeois M, Draye JP. Evidence of a preprogrammed deactivation of the hamstring muscles for triggering rapid changes of posture in humans. Electroenceph Clin Neurophysiol. 1997;105:58–71.
8. Valdeci Carlos Dionisio, Gil Lucio Almeida, Marcos Duarte, Rogerio Pessoto Hirata Kinematic, Kinetic and EMG patterns during downward squatting, Journal of Electromyography and Kinesiology 2008;18:134-143.
9. Escamilla, RF. Knee biomechanics of the dynamic squat exercise. Med Sci Sports Exerc. 2001;33:127–141, 2001.
10. Yasuda, K., and T. Sasaki. Exercise after anterior cruciate ligament reconstruction: the force exerted on the tibia by the separate isometric contractions of the quadriceps or the hamstrings. Clin.Orthop.1987; 220:275–283.
11. Senter C, Hame SL. Biomechanical analysis of tibial torque and knee flexion angle: Implications for understanding knee injury. Sports Med. 2006;36:635–641.
12. Shields RK, Madhavan S, Gregg E, Leitch J, Petersen B, Salata S, et al. Neuromuscular control of the knee during a resisted single-limb squat exercise. Am J Sports Med. 2005;33:1520-6.
13. Toutoungi, D.E., T.W.Lu, A. Leardini, F. Catani, and J.J. O'Connor. Cruciate ligament forces in the human knee during rehabilitation exercises. Clin. Biomech. 2000;15:176 –187.
14. Elias JJ, Faust AF, Chu Y, Chao EY, Cosgarea AJ. The soleus muscle acts as an agonist for the anterior cruciate ligament: an in vitro experimental study. Am J Sports Med. 2003;31:241-6.
15. Stuart MJ, Meglan DA, Lutz GE, Growney ES, An KN. Comparison of intersegmental tibiofemoral joint forces and muscle activity during various closed kinetic chain exercises. Am J Sports Med. 1996 Nov-Dec;24(6):792-9.
16. Li, G, DeFrate, LE, Rubash, HE, and Gill, TJ. In vivo kinematics of the ACL during weight bearing knee flexion. J Orthop Res 2005;23:340-344.
17. Kreighbaum, E., Katharine, B.M., Biomechanics; A Qualitative Approach for Studying Human Movement, Allyn & Bacon. 1996;Pgs 203-204.

18. Donnelly, DV, Berg, WP, and Fiske, DM. The effect of the direction of gaze on the kinematics of the squat exercise. J Strength Cond Res. 2006;20:145–150.

19. Cholewicki, J., Juluru, K., McGill, S. Intra-abdominal Pressure Mechanism for Stabilizing the Lumbar Spine. Journal of Biomechanics 1999;32:13-17.

20. Richardson C., Jull G., Hodges P. and Hides J. Therapeutic Exercise For Spinal Segmental Stabilization In Low Back Pain - Scientific Basis And Clinical Approach. London, New York, Philidelphia, Sydney, Toronto: Churchill Livingstone,1999, 6 p. 55-58.