THESIS OF PHD DISSERTATION

Biomechanical exploration of lower extremity injury mechanism during table tennis topspin forehand and implication for skills optimization and motor control

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SCIENTIFIC BACKGROUND AND OBJECTIVES

Scientific Background

As one of the most popular racket sports, table tennis is not only loved by people all over the world in the field of public health but also receives widespread attention in the Olympic Games and competitive competitions. With the redesign of the size and material of table tennis balls and the adjustment of competition rules, the competitiveness of this sport has been further improved. After the size of the table tennis ball was adjusted to 40+, due to the increase in volume, the rotation speed of the ball decreased, which directly affected the development and application of the skills, tactics, and technology of this sport. Affected by the current rules, this sport is becoming more and more suitable for players who are good at forehand attack style or have more comprehensive skills. This makes table tennis players pay more attention to the development of physical function and muscle strength than ever before, and expect to enhance their aggression by increasing their hitting power to help score points. Therefore, in recent years, the biomechanical mechanism of forehand topspin has received a lot of attention and research from a large number of scholars. Due to the enhancement of competitiveness and the improvement of physical function requirements, sports fatigue occurs more frequently during competition. Frequent exercise fatigue leads to the occurrence of acute injuries. In addition to acute injuries, overuse of the body due to extensive training and competition tasks among professional athletes has been proven to be a major injury factor in racket sports. Acute injuries in table tennis and injuries caused by overuse often occur in the lower limb joints, lower limb trunk, and shoulders, which greatly limits the sports life and performance of elite athletes. The execution of tactics and the stable performance of technology are key factors for athletes to win in competitions. In table tennis, a perfect stroke play is the basic condition for scoring, which requires athletes to strengthen the movement control of the body and enhance the coordination and stability of the body. The ability to maintain body balance is an external manifestation of an athlete's body control and stability. The main thing that table tennis players need is to reach the designated area in a very short time to complete the hitting task. Due to the continuous improvement of competition level and changes in competition rules, the flight speed of the ball continues to increase, making players need to complete the hitting task in a shorter time. This further results in athletes often needing to maintain body balance and stability under extreme circumstances. However, this situation aggravates the occurrence of acute injuries.

Table tennis is generally considered a low-injury risk sport, which has led to a large amount of past research focusing on performance improvements. However, serious sports injuries are widespread among top table tennis players. The prevention of sports injuries and the improvement of movement control are also factors that cannot be ignored by athletes and coaches. Exploring the internal mechanical mechanisms and injury mechanisms of table tennis topspin forehand and footwork from a biomechanical perspective could provide useful information for sports medicine and motor control, and could also provide a reference for table tennis footwear development and therapeutic equipment. The use of musculoskeletal modeling has been prevalent in the past 10 years in the biomechanics field, because of its ability to evaluate muscle and joint reaction forces during functional activities. In conclusion, this

study uses a series of different biomechanical experiments and computer simulations to import experimental data into OpenSim to implement musculoskeletal simulation to explore the mechanical characteristics and possible injury risks of the lower limb trunk and joints in table tennis topspin forehand and footwork. The coach and athlete could acquire valuable information to optimize training strategy and enhance motor control. Relevant researchers could quickly establish a basic understanding and knowledge through this study.

Scientific Objectives

1st objective:

The first research objective: Based on subject-specific musculoskeletal modeling and simulations to explore the injury risk and motor control strategy of table tennis footwork and guide the footwear design.

2nd objective:

Explore the cryotherapy effect on balance recovery after fatigue to guide the cryotherapy equipment design and applications.

3rd objective:

Reveal the intrinsic biomechanical mechanism of topspin forehand stroke, provide guidance for optimization.

THESIS POINTS

1st Thesis point:

I provided the first hybrid model (Gait2392 musculoskeletal model in OpenSim together with a Novel Pedar insole plantar pressure measurement system) for detecting lower extremities injury areas.

First, using experiments I could prove that the highest peak pressures appear in the medial-lateral rear foot and the lateral forefoot during the backward phase if one-step movement is considered[1]. Concerning the chasse-step, the most dangerous area for possible injury was found to be the toe during the forward phase (as shown in Figure 1).

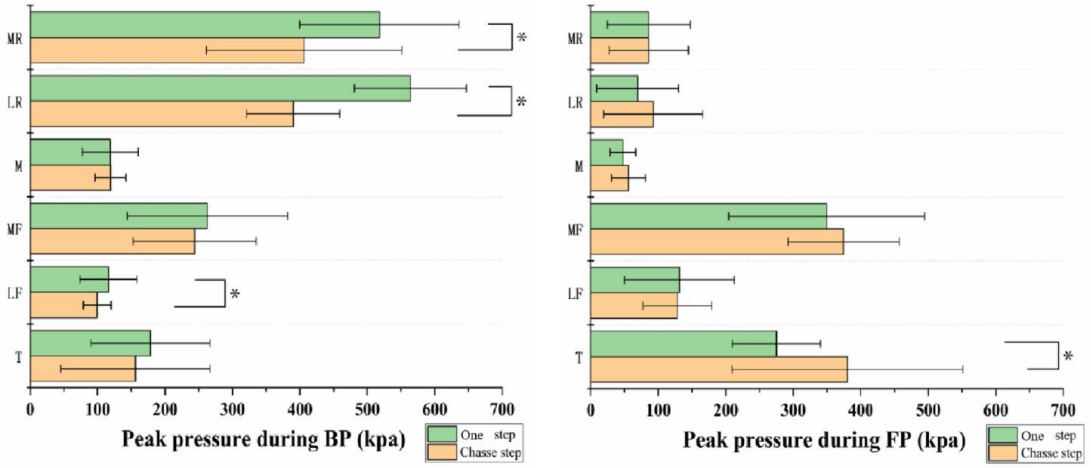

Figure 1. Comparison of peak pressure of each plantar region during BP and FP. Note: The asterisk (*) refers to significance with $p < 0.05$.

Second, the activation and the behavior of eight major muscles (as shown in Figure 2) were characterized in the OpenSim model as a function of the stroke phase and validated by electromyography measurements[2]. Based on these force characteristics one can deduce that at what percentage of the stroke may the major muscles reach their maximum activity, which can be plausible for injury. These force responses provide valuable information to sports coaches when strategies for muscle strengthening in table tennis are considered.

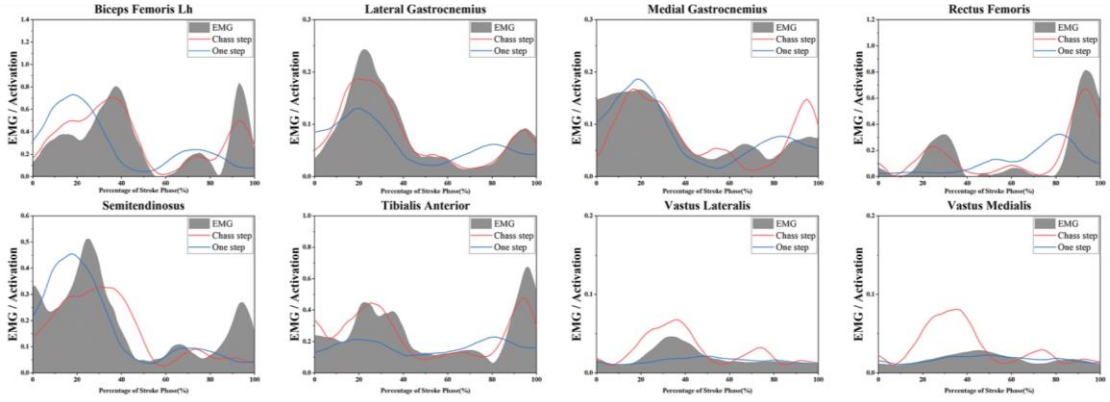

Figure 2. Comparison of lower extrimities muscle sEMG signals and activations from OpenSim Optimization between the chasse step and one-step during stroke in table tennis.

Third, the joint stiffness of the lower limb during the landing stage was simulated and calculated[3] (as shown in Figure 3), which could investigate the intrinsic mechanical mechanism during the landing process, can report the possible areas where injury may occur.

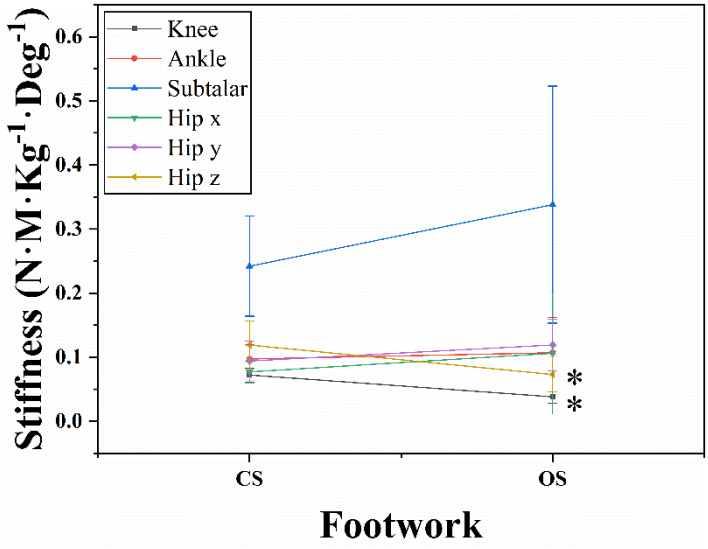

Figure 3. Lower limb joint stiffness during the landing stage in the chasse step and one-step footwork.

Related articles to the 1st thesis point:

[1] **He, Y.,** Sun, D., Yang, X., Fekete, G., Baker, J. S., & Gu, Y. (2021) Lower limb kinetic comparisons between the chasse step and one step footwork during stroke play in table tennis. PeerJ, 9, e12481. (Q1, IF: 3.061)

[2] **He, Y.,** Shao, S., Fekete, G., Yang, X., Cen, X., Song, Y., Sun, D. & Gu, Y. (2023) Lower Limb Muscle Forces in Table Tennis Footwork during Topspin Forehand Stroke Based on the OpenSim Musculoskeletal Model: A Pilot Study. Molecular & Cellular Biomechanics, 19(4), 221–235. (EI, Scopus)

[3] **He, Y.,** Zhang, P., Gao, Z., Yang, X., Fekete, G., Kovács, A., & Gu, Y. (2024) Joint reaction force and stiffness during the landing stage in table tennis footwork. The 29th European Society of Biomechanics. Edinburgh, Scotland

2nd Thesis point:

I have developed and produced portable cryotherapy equipment for the recovery of lower limb fatigue in professional table tennis players[1,2]. As shown in Figure 4, I calculated and confirmed that 1) from the 24h post-intervention, the effect of cryotherapy on dynamic balance recovery was significantly better than no cryotherapy; 2) Except for the COP maximum displacement on ML at the 72h post-intervention, the cryotherapy had no positive effect on the recovery of static balance ability; 3) Cryotherapy has a significant negative impact on the COP maximum displacement in ML and AP at the post-cryotherapy, which may lead to the decline of static balance ability. Therefore, it was not recommended to use cryotherapy for balance recovery if the competition was on the same day or within 24 hours. Cryotherapy was recommended if the competition was on the next day or after the next day.

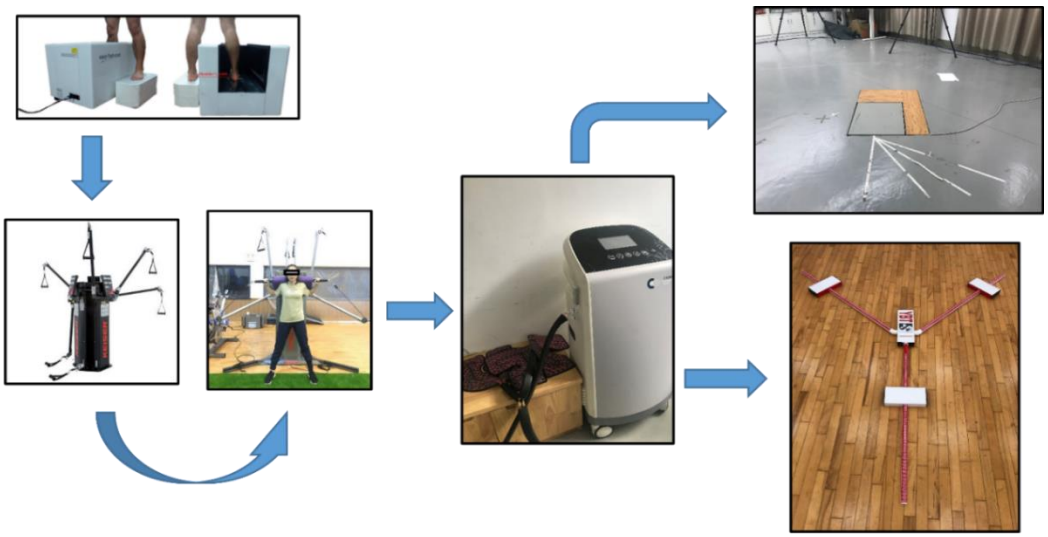

Figure 4. The biomechanics exploration flowchart of the cryotherapy effect on balance ability after lower extremity fatigue.

Related articles to the 2nd thesis point:

[1] **He, Y.,** & Fekete, G. (2021). The Effect of Cryotherapy on Balance Recovery at Different Moments after Lower Extremity Muscle Fatigue. Physical Activity and Health, 5(1). (Scopus)

[2] Lu, Y., **He, Y.,** Ying, S., Wang, Q., & Li, J. (2021). Effect of Cryotherapy Temperature on the Extension Performance of Healthy Adults' Legs. Biology, 10(7), 591. (**Q1,** IF: 5.168)

3rd Thesis point:

As a first researcher in the field, I have given a complete kinematic and kinetic description of the lumbar movement concerning cross-court and long-line topspin forehand using computational simulation and experiments[1].

In the kinematic data, I explored for the first time how the lumbar axial rotation, left lateral bending, and flexion movement behaviors as a function of the stroke play phase. It is visible from the results that the cross-court topspin forehand has slightly higher (cca.15%) values throughout the motion (as shown in Figure 5).

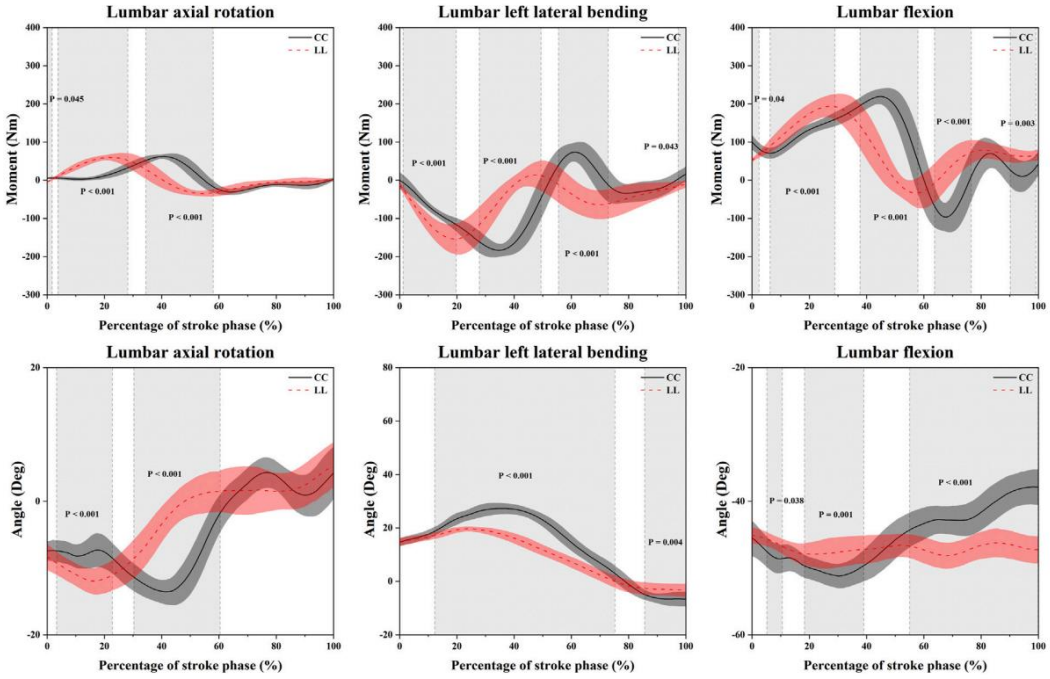

Figure 5. The simulation results of the lumbar angle and moment during cross-court and long-line topspin forehand.

Besides the kinematic data, important findings can be deducted from the kinetic results as well. As shown in Figure 6, the cross-court topspin forehand has a significant effect during lumber flexion (cca.14% higher moment than during long-line topspin forehand) and lumbar left lateral bending (cca.16% higher moment than during long-line topspin forehand). It can be assumed that this increased, and suddenly appearing load on the spine can be the root of lower back pain in the long term.

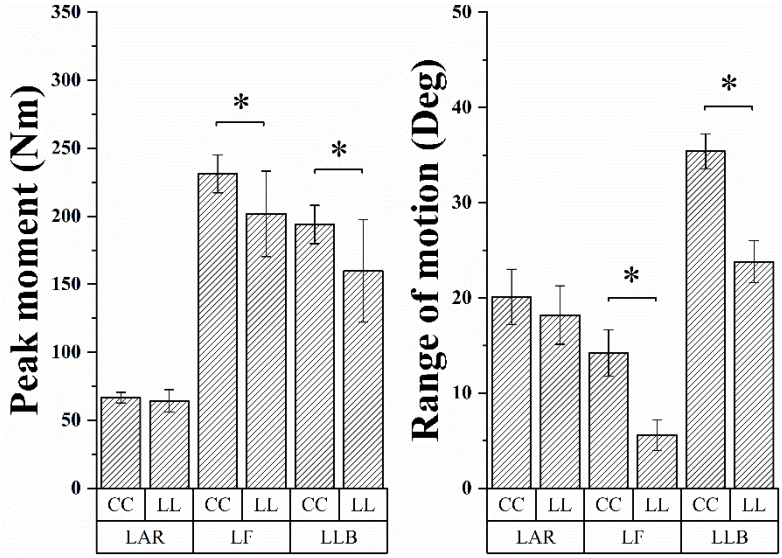

Figure 6. The Rom and peak moment comparison of lumbar movement between the CC and LL topspin forehand. (Note: "*" indicates a significant difference between LL and CC.)

Related articles to the 3rd thesis point:

[1]**He, Y.,** Liang, M., Fang. Y., Fekete, G., Baker, J. S., & Gu, Y. (2023) Lumbar and pelvis movement comparison between cross-court and long-line topspin forehand in table tennis: based on musculoskeletal model. Frontiers in Bioengineering and Biotechnology, 11, 1185177. (Q1, IF: 5.7)

SCIENTIFIC PUBLICATIONS

Referred articles related to this thesis:

1. He, Y., Liang, M., Fang. Y., Fekete, G., Baker, J. S., & Gu, Y. (2023) Lumbar and pelvis movement comparison between cross-court and long-line topspin forehand in table tennis: based on musculoskeletal model. Frontiers in Bioengineering and Biotechnology, 11, 1185177. (Q1, IF: 5.7)

2. He, Y., Fekete, G., Sun, D., Baker, J. S., Shao, S., & Gu, Y. (2022). Lower Limb Biomechanics during the Topspin Forehand in Table Tennis: A Systemic Review. Bioengineering, 9(8), 336. (Q2, IF: 5.046)

3. He, Y., Shao, S., Fekete, G., Yang, X., Cen, X., Song, Y., Sun, D. & Gu, Y. (2023) Lower Limb Muscle Forces in Table Tennis Footwork during Topspin Forehand Stroke Based on the OpenSim Musculoskeletal Model: A Pilot Study. Molecular & Cellular Biomechanics, 19(4), 221–235. (EI, Scopus)

4. He, Y., Lyu, X., Sun, D., Baker, J. S., & Gu, Y. (2021). The kinematic analysis of the lower limb during topspin forehand loop between different level table tennis athletes. PeerJ, 9, e10841. (Q1, IF: 3.061)

5. He, Y., Sun, D., Yang, X., Fekete, G., Bak er, J. S., & Gu, Y. (2021). Lower limb kinetic comparisons between the chasse step and one step footwork during stroke play in table tennis. PeerJ, 9, e12481. (Q1, IF: 3.061)

6. He, Y., & Fekete, G. (2021). The Effect of Cryotherapy on Balance Recovery at Different Moments after Lower Extremity Muscle Fatigue. Physical Activity and Health, 5(1). (Scopus)

7. Lu, Y., **He, Y.,** Ying, S., Wang, Q., & Li, J. (2021). Effect of Cryotherapy Temperature on the Extension Performance of Healthy Adults' Legs. Biology, 10(7), 591. (Q1, IF: 5.168)

8. Yang, X., Mei, Q., Shao, S., Gu, W., **He, Y.,** Zhu, R., & Gu, Y. (2022). Understanding Sex-Based Kinematic and Kinetic Differences of Chasse-Step in Elite Table Tennis Athletes. Bioengineering, 9(6), 246. (Q2, IF: 5.046)

International conference abstracts related to this thesis:

1. Yuqi He, Zixiang Gao, Gusztáv Fekete, András Kovács, Dusan Mitic, and Yaodong Gu. Lower lime muscle forces in table tennis footwork during topspin forehand based on musculoskeletal. The 28th European Society of Biomechanics. 2023. Maastricht, Netherlands

2. Yuqi He, Zixiang Gao, Gusztáv Fekete, András Kovács, Aleksandar Nedeljkovic, Dusan Mitic, and Yaodong Gu. Lumbar and Pelvis Movement Comparison between Cross-court and Long-line Topspin Forehand Stroke: Based on Musculoskeletal Model. The 50th International Society of Biomechanics. 2023. Fukuoka, Japan

3. Yuqi He, Zixiang Gao, Gusztáv Fekete, Dusan Mitic, and Yaodong Gu. Plantar force comparisons between the chasse step and one step footwork during topspin forehand using statistical parametric mapping. The 40th International Society of Biomechanics in Sports Proceedings Archive. 2022. Liverpool, England

4. Yuqi He, Zixiang Gao, Gusztáv Fekete, Dusan Mitic, Yaodong Gu. The effect of cryotherapy on balance recovery at different moments after lower extremity muscle fatigue. The 27th European Society of Biomechanics. 2022. Porto, Portugal

5. Yuqi He, Penghui Zhang, Zixiang Gao, Xiaoyi Yang, Gusztáv Fekete, András Kovács, and Yaodong Gu. Joint reaction force and stiffness during the landing stage in table tennis footwork. The 29th European Society of Biomechanics. 2024. Edinburgh, Scotland

Other publications:

1. **He, Y.,** Lv, X., Zhou, Z., Sun, D., Baker, J. S., & Gu, Y. (2020). Comparing the kinematic characteristics of the lower limbs in table tennis: Differences between diagonal and straight shots using the forehand loop. Journal of sports science & medicine, 19(3), 522. (Q1, IF: 4.017)

2. Zhou, H., **He, Y.,** Yang, X., Ren, F., Ugbolue, U. C., & Gu, Y. (2021). Comparison of Kinetic Characteristics of Footwork during Stroke in Table Tennis: Cross Step and Chasse Step. JoVE (Journal of Visualized Experiments), (172), e62571. (Q2, IF: 1.355)

3. Yang, X., **He, Y.,** Shao, S., Baker, J. S., István, B., & Gu, Y. (2021, June). Gender Differences in Kinematic Analysis of the Lower Limbs during the Chasse Step in Table Tennis Athletes. Healthcare 9, 703. (Q2, IF: 3.160)

4. Lv, X., **He, Y.,** Sun, D., Baker, J. S., Xuan, R., & Gu, Y. (2020). Effect of stud shape on lower limb kinetics during football related movements. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 234(1), 3 10. (Q3, IF: 1.263)

5. Shen, S. Q., **He, Y. Q.,** Zhang, Y., Fekete, G., & Zhou, Z. X. (2020). Biomechanical analysis of long distance running on different sports surfaces. In Journal of Biomimetics, Biomaterials and Biomedical Engineering 45, 31 39. (EI, Scopus)

6. Yuqi He, Changxiao Yu, Zhiqiang Liang, Zhexiao Zhou, Yaodong Gu. Comparing the kinematic characteristic between diagonal and straight shot in forehand loop from world class table tennis athlete. 16th ITTF Sports Science Congress Sports Science Committee. 2019. Budapest, Hungary

7. Yuqi He. A review of research methods of lower extremity resistance exercise in middle aged and old people. The 3rd International Forum on Sport and Health. 2018. Ningbo, China

8. Gao Zixiang, **He Yuqi,** Xiang Liangliang, Fekete Gusztáv, Kovács András, and Gu Yaodong. Automatically detecting fatigue gait based on time series bilateral plantar force distribution using deep learning algorithms. The 28th European Society of Biomechanics. 2023. Maastricht, Netherlands

9. Gao Zixiang, **He Yuqi,** Fekete Gusztáv, Gu Yaodong. Effects of running fatigue on knee joint symmetry among amateur runners. The 40th International Society of Biomechanics in Sports Proceedings Archive. 2022. Liverpool, England

10. Zixiang Gao, **Yuqi He,** Gusztáv Fekete, Yaodong Gu. The effect of the running-induced fatigue on the symmetry of kinematics and kinematic variables of knee joint in a counter movement jump. The 27th European Society of Biomechanics. 2022. Porto, Portugal

11. Zhiqiang Liang, Changxiao Yu, **Yuqi He,** Xiang Lv, Yaodong Gu. The kinematics analysis of stride step of elite table tennis player. 16th ITTF Sports Science Congress Sports Science Committee. 2019. Budapest, Hungary

12. Changxiao Yu, Shi rui Shao, Zhiqiang Liang, **Yuqi He,** Yaodong Gu. The biomechanical effects of

two performance levels during table tennis cross step. 16th ITTF Sports Science Congress Sports Science Committee. 2019. Budapest, Hungary

Reviewer for International Journal Articles:

1. PloS One
2. Computer Methods in Biomechanics and Biomedical Engineering
3. International Journal of Biomedical Engineering and Technology
4. BMC Sports Science, Medicine and Rehabilitation
5. Frontiers in Bioengineering and Biotechnology
6. Sport Sciences for Health
7. Physical Activity and Health
8. PeerJ
9. Frontiers in Physiology
10. Frontiers in Psychology
11. Applied Bionics and Biomechanics
12. Frontiers in Sports and Active Living

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