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The Influence of Biomechanical Factors on Belle Piked Highly Executed Gymnastic Performance on the Parallel Bars

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Abstract: The purpose of this study was to identify the correct technique to perform highly executed long swing gymnastic movement: Belle Piked (BP). Two national Chinese gymnasts (58kg, 60.3kg) performed 4 repetitions of BP movement, on the middle of parallel bars with zero deduction. Reflective markers (14mm) and ten high-speed cameras (ViconT40S, 100Hz) were used to observe the time history of attached markers on the Humeral head and Cervical Vertebra (C7). The coordinates of the necessary markers were observed using ViconT40S digitizing software. Standard Lagrange dynamic equations were used to derive the dynamic equations of Arm. The average stiffness coefficient of the shoulder joints ($K_{S,Avg}$ = 31,670 $N.m^{-1}$) was estimated through the model of the shoulder. The reaction on the Humeral head ($R_{S,Avg}$ = 196.14 N) under the bars (angular displacement of C.G is 180°) is significantly lower than the other places of the movement pattern. Also, the direction of acceleration of the Humeral head (-2.88 $m.s^{-1}$) implied that the player moves the body upward with respect to the C7. The range of muscle torque around the shoulder joint is $-10.8\ N.m < \tau_s < +\ 18.2\ N.m$. Though the angle of the head and neck segment with the vertical axis is nearly zero at the bottom of the bars, the gain of elastic energy from bars was optimized (122.75 J for 58 kg player). Therefore, optimum values of these biomechanical factors are influenced to promote BP movement on the parallel bars with zero execution errors.

Keywords: Elastic Energy, Execution Errors, Model of Shoulder

1. Introduction

The long swing elements on the parallel bars in Men's Artistic Gymnastic are performed by players to increase their difficulty value in competitions. Therefore, players pay more attention to their body coordination during entire long swing movements on the parallel bars (PB) apparatus. When the player reaches the vertical position under the bars, the player obtains the maximum amount of kinetic energy. Hence, flexible bars bend and store some of the energy in response to the player's actions (Figure 1).

Parallel bars' movements interact with joint torques of the gymnast's body and resulting in linear and angular momentums [1, 11]. The tops of the metal posts also interact with long swing movements. Therefore, to enhance the performance, gymnasts need to consider not only the movements of wooden PB but also how the tops of metal posts move corresponding to the long swing elements is questionable in the teaching-learning process of Belle-type elements.

That being the case, most gymnastic players face several difficulties (release phase, momentary phase, and follow-through) to read the correct techniques of gymnastic elements. In the preparatory period, coaches inform their players to "push" the bars or "pull" the bars, but coaches and players are unable to predict the exact value of force and its direction, and at what time it should be done. These facts depend on the experience of the coach and the player's skill adaptation.

Performing Balle-type Gymnastic movements on the parallel bars with zero deduction is a critical part of the exercise routine in the competition. The reason is the verity of evaluations that were introduced by FIG for saltos elements on the PB: lack of extension at horizontal regrasping after saltos

(0.1 or 0.3 execution errors); uncontrolled regrasping after saltos (0.3 or 0.5 execution errors) [6]. Though gymnasts mainly tried to optimize the rotation speed of the body to overcome these execution errors, most the National level Chinese coaches believe that optimization of kinetic variables of the gymnast-parallel bars system also affects to occur proper landing of BP movement on the parallel bars. Therefore, gymnast essentially needs to study the body dynamic which is interacted with their BP movements.

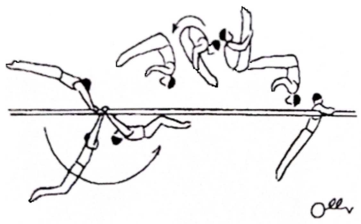

Figure 1. *BP: forward giant swing backward double salto piked to upper arm hang [6].*

Especially, the behaviour of shoulder joints through the Belle-type movements under the PB is unpredictable for a player and coach. The majority of national gymnasts may try to apply maximum force at the bottom of the bars. Therefore, landing on the bars may not be perfect to avoid execution errors. Also, few Olympic players in China responded, that they may not apply maximum force at the bottom of the bars. However, Olympic coaches believed that preparing the flexible shoulders near the bottom of the bars is effective to complete accurate Belle-type movements. Few coaches do not have a precise mechanism to describe the shoulder movements of a gymnast. As a solution to this problem, the biomechanical model of the arm [2] was used to investigate biomechanical factors of the gymnast-parallel bars system based on the performance of BP with zero execution errors.

2. Methodology

To design a biomechanical model of the gymnast-parallel bars system, firstly the PB was modelled to measure dynamic properties [4]. Secondly, the gymnast shoulder model was designed based on the kinetics and kinematics of gymnast body segments [2, 10]. Standard Lagrange dynamic equations were used to derive the dynamic equations of Arm (hand, upper arm, and forearm) 3 segments models. Standard Chinese anthropometric measurements were considered to find the characteristics of 14 segments body models [12]. The Gleno-Humeral joints of a gymnast were modelled with massless spring-dampers to observe the adapted kinematics on the frontal frame of the gymnastic-parallel bars system [9]. A 3D mathematical model was used to observe the dynamic properties of wooden bars [4]. Two national-level gymnasts of China (58 kg and 60.3 kg) performed four repetitions of a long swing movement: BP, under four different conditions on the middle of PB as shown in figure 1.

Reflective markers (14 mm) and ten high-speed cameras (ViconT40S, 100 Hz) were used to observe the time history of attached markers on the PB and subjects. The coordinates of necessary markers were calculated using ViconT40S digitizing software. Hence, kinematics and kinetics values were calculated using Matlab R2014b software and estimated the parameters of spring dampers of the model of the shoulder. Using standard Lagrange Equation, 3 dynamic equations of the motion of the shoulder-parallel bars system were derived cause to the 4 degrees of freedom (r, θ, β, and θ_Y) of the system. The least-square curve fitting technique was used to find the equations of smooth curves of four variables of the dynamic shoulder-parallel bars system. The first and second derivatives of equations represent velocities and accelerations respectively [13].

Visco Elastic Gleno-Humeral Joint of Gymnast: To calculate the reaction force on H and muscle torque around the shoulder: The proximal end of the Upper Arm of the player, and the free body diagram of the straight Arm were considered (Figure 2(b)) [14, 15]. Dynamic equations (1), (2), and (3) were derived using the Lagrange Equation. The following Figure 2(a) shows a 3D view of arms' movement at time t of the element BP (Figure 1).

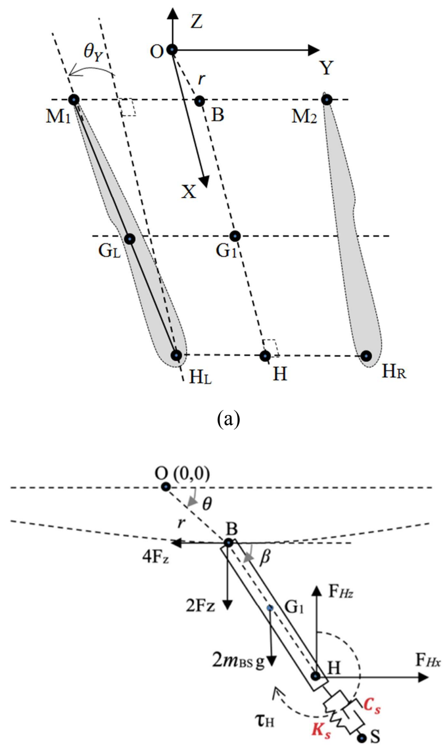

Figure 2. *(a): Gymnast's two arms (arm→hand+lower arm+upper arm) represent from M_1H_L and M_2H_R at time t of the element (Figure 1). H is the middle point of H_L and H_R. B and H are always on XY-plane throughout the element. OB = r same as shown in Figure 1. G_1 is the center of mass of both arms on XZ-plane. G_L is the center of mass of left arm of the player. (b): Free body diagram of the Arms (mass: $2m_{BS}$) of the player on XZ-plane (sagittal plane of gymnast-parallel bars system) of the shoulder-parallel bars System at time t = t. F_{Hx} and F_{Hz} are components of the reaction force (R) on proximal end of the Upper Arm. τ_H is a muscle torque around the shoulder joint. HS (= p) reagent has a massless spring-damper (K_s and C_s are spring-damp coefficients) to represent visco elastic properties of Gleno-Humaral joint of gymnast relevant to the long swing movement: BP. O (the middle point of the parallel bars) is an origin of the 2D coordinates system.*

Let BH= l_{BH}, the length of an arm on the XZ-plane.

$M_1H_L = M_2H_R = l_{M_1G_L}$, and $l_{BH} = l_A \cos\theta_Y$, Where l_A is the actual length of an arm.

Using L = T – V, where T and V are kinetic energy and potential energy respectively

$$L = \frac{1}{2} I_{G1}\, \dot{\beta}^{\,2} + \frac{1}{2}(2m_{BS})\{[\dot{r}\cos\theta - r\dot{\theta}\sin\theta - l_{M_1G_L}(\dot{\beta}\sin\beta\,\cos\theta_Y + \dot{\theta}_Y\sin\theta_Y)]^2 + [\dot{r}\,\sin\theta + r\dot{\theta}\cos\theta$$

$$- l_{M_1G_L}(-\dot{\beta}\,\cos\beta\cos\theta_Y + \dot{\theta}_Y\sin\theta_Y\sin\beta)]^2\} - 2m_{BS}\, g\,(r\sin\theta + l_{M_1G_1}\cos\theta_Y\,\sin\beta) + \frac{1}{2}K_s(p)^2$$

Force on the point B = $-4F_X$ I–$2F_Z$ K; OB = $r\cos\theta$ I – $r\sin\theta$ K

Force on the point H = F_{HX} I + F_{HZ} K; OH = $(r\cos\theta + l_A\cos\beta)$I – $(r\sin\theta + l_A\sin\beta)$ K

Applying Lagrange equations [13] for straight shoulder Arms;

$$\frac{d[\frac{\delta L}{\delta \dot{r}}]}{dt} - \frac{\delta(L)}{\delta r} = Qr = 2m_{BS}\,\{\ddot{r} - l_{M_1G_1}[\ddot{\beta}\,\sin(\beta-\theta) + \dot{\beta}^2\cos(\beta-\theta)] - r\,\dot{\theta}^2 - g\sin\theta\}$$

$$Qr = -(4F_X - F_{HX})\cos\theta + (2F_Z - F_{HZ})\sin\theta \quad (1)$$

$$\text{Similarly; } (4F_X - F_{HX})\, r\sin\theta + (2F_Z - F_{HZ})\, r\cos\theta = 2m_{BS}\,\{2r\dot{r} + r\ddot{\theta} + l_{M_1G_1}[-(r\dot{\beta}^2 + r\dot{\theta}\dot{\beta})\sin(\beta-\theta)] + r\ddot{\beta}\cos(\beta-\theta)\} \quad (2)$$

$$(F_{HX}\sin\beta + F_{HZ}\cos\beta)\, l_A = -(I_B + 2m_{BS}\, l_{M1G1}^2)\,\ddot{\beta} + 2m_{BS}\, l_{M_1G_1}[\ddot{r}\sin(\beta-\theta) + r\ddot{\theta}\cos(\beta-\theta) + r\dot{\theta}^2\sin(\beta-\theta) + g\cos\beta] \quad (3)$$

Substituting all required variables (r, β, θ, 1st and 2nd derivatives of r, β, and θ) to equations (1), (2), and (3), the reaction force ($\sqrt{F_{HZ}^2 + F_{HX}^2}$) was calculated.

Two markers are attached to two points: the Cervical Vertebra (C7) and the Head of the Humerus (a marker attached near to the Greater Tubercle). These two points were considered to calculate the displacement of H from S (= p) as shown in Figure 2(b). Assumed the displacement of H from C7 is zero at t=0 (handstand position on PB) in the dynamic movement of BP (Figure 1).

K_s and C_s were estimated using the least-squares are curve fitting (Mathlab14b software) of the formulated spring-damper forces [2].

The moment of inertia of an Arm around the proximal end of the Upper Arm (H) is

$$I_H = \frac{1}{3}(m + M)(L + l)^2 \qquad \text{(Source: [5])} \quad (4)$$

Where m, M, L, and l are mass of fits, the mass of 'Forearm+Upper Arm', length of fits, and length of 'Forearm+Upper Arm', respectively [5].

The angle between the straight Arm and 'Upper Torso+Lower Torso' = [β+(90-θ_S)], where θ_S is the angle of the trunk from the vertical axis through S.

Therefore, Muscle torque around the shoulder joint

$$(\tau_S) = -\, I_H\,(\ddot{\beta} - \ddot{\theta}_S) \quad (5)$$

The total energy of the parallel bars at the time t of the long swing movement is E_{total}. The total kinetic energy of 4 spring dampers of the 3D mathematical model of a bar was considered to calculate the elastic energy of the parallel bars at time t = t s in the dynamic movement [2, 3]. To calculate the total strain energy (E_{total}) of the bars in the dynamic situation, the 3D mathematical model of parallel bars [2] was considered.

$$E_{total} \approx 2\, r^2\,(\frac{1}{2}\, 2K_x\, \sin^2\theta + \frac{1}{2}K_Y\, \sin^2\theta_Y + \frac{1}{2}\, K_z\, \cos^2\theta) \quad (6)$$

Where K_y and K_z represent the stiffness coefficients of wooden parallel bars in Y and Z directions, respectively. The K_x coefficient is interpreted as elastic properties of the metal post of the parallel bars.

3. Result and Discussion

The norms of the Federation of International Gymnastic demand vertical midpoint stiffness to be within the range of 19,000-27,400 $N.m^{-1}$ [16]. The vertical midpoint stiffness (K_z) value was calculated in the dynamic situation of the parallel bars (19,101 $N.m^{-1}$) using oscillation of 50 kg solid spear [3]. The same procedure was used to calculate K_y (10,830 $N.m^{-1}$) and K_x (28,601 $N.m^{-1}$) [2].

The average stiffness coefficient of the shoulder joints ($K_{S,Avg}$=31,670 $N.m^{-1}$) was estimated through the model of shoulder: equation (1), (2), and (3). The minimum value of reaction force on the Humeral head ($R_{S,Avg}$) is 196.14 N at t=0.68s (angular displacement of C.G is nearly 180^0).

From equation (4); I_H values for two gymnasts (58 kg and 60.3 kg) are 0.7499 $kg.m^{-2}$ and 0.7521 $kg.m^{-2}$. From equation (5); The range of muscle torque around the shoulder joint is -10.8 N.m < τ_S < + 18.2 N.m as shown in Figure 3 (mass of the player is 58 kg).

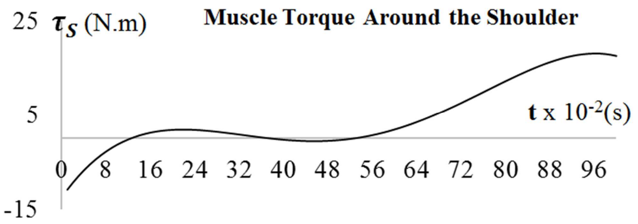

Figure 3. *The muscle torque around the shoulder, the angle between Upper Body and Arm is (β+90-θ_S).*

The shoulder kinematics and kinetics describe the specific dynamic movement pattern of shoulder movements that interact with the BP. The gymnast starts long swing movement with a stable handstand position on the parallel bars (p ≈ 0, Figure 4).

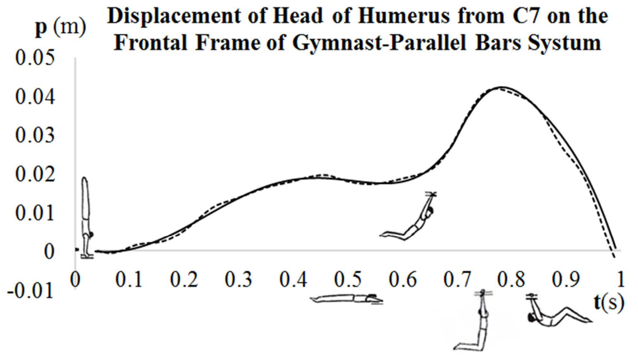

Figure 4. *Solid line represents smooth curve of displacement (p) of H from S. Dashed line represents experimental data of p (mass of the gymnast is 58 kg).*

After that, the gymnast extends his entire body with flex shoulders (no more than 180°) and chest-in position (C-shape of the posterior side of the upper body). In this period, the range of relative displacement of the Head of the Humerus from the C7 is 0 – 0.1175 m and the muscle torque is very small. After the first 90° of the motion, the gymnast improved muscle torque until 18.11 N.m. However, at the bottom of the motion, players maintain the soft shoulders with the lowest reaction force (8.17 N ≤ R ≤ 410.26 N) on the Head of the Humerus. The reaction force on the Head of the Humerus is 194.45 N at the bottom of the motion (197.83 N for 60.3 kg mass). Just after releasing the bars, muscle torque, and reaction force improved significantly to prepare the body for the rotation. Before releasing the bars Head of the Humerus shows the maximum relative displacement from the C7 as 0.0423 m at 0.78 s of the motion. The 3D biomechanical model consists of a linear spring-damper between C7 and the Head of the Humerus to examine the elastic behavior of shoulder joints on the XZ plane. The gymnast (58 kg) has a 32,048 N.m^{-1} stiffness coefficient to perform the BP (K_s = 31,292 N.m^{-1} for 60.3 kg).

The stiffness coefficient K_s of the shoulder for the BP movements were increased from 0 to 31,670 N.m^{-1}. This range of stiffness coefficient of the shoulder is almost similar to the findings of Hiley M [8] for under somersault on the parallel bars: 0 to 30,000 N.m^{-1}. However, dynamic movements of the proximal end of the Humerus bone play a dominant role under the bars to acquire the maximum amount of elastic energy of the parallel bars as shown in Table 1. When the player reaches the exact vertical position of the body under the bars, the middle point of a bar moves about 15 mm towards the body on the sagittal plane. This is a considerable amount of force generation (150.2 N from a bar) for 58 kg mass player (Figure 6).

Table 1. *The Comparison between shoulder movement (H) and gain elastic energy of parallel bars.*

t (s)	*p* (m)	Gain Elastic Energy of Parallel Bars (J)
0.72	0.0350	122.75 (max)
0.78	0.0422	113.75 (max)

Figure 6 shows the dynamic force (Z-component) which is acting on the point B while the player (mass 58 kg) was performing BP movement between the middle points of the parallel bars: 180 cm height of the wooden bars from the mat [7]. The player gains the maximum amount of elastic energy of bars (122.75 J, at t=0.72 s) when the body reaches the exact vertical position under the wooden parallel bars (Fz = 1,254.4 N at the t= 1.74 s; the same body position represents in figures 3, 4 and 5 at t=0.72 s). To gain the elastic energy of the bars, the player used special shoulder movement as shown in Figure 3 and Figure 5. Although the maximum energy of parallel bars is stored at the bottom of the movement, the shoulders have to control the muscle torque (7.6 N). The shoulder movement near the bottom of the movement is significantly different with respect to the reaction force on H (Figure 5). That is a 44.8 N value at 0.68 s near the bottom of the movement. The aforementioned kinematics and kinetics variables (Table 2) of the Visco Elastic Gleno-Humaral (VEGH) joint were demonstrated in order to perform zero deduction element BP on PB.

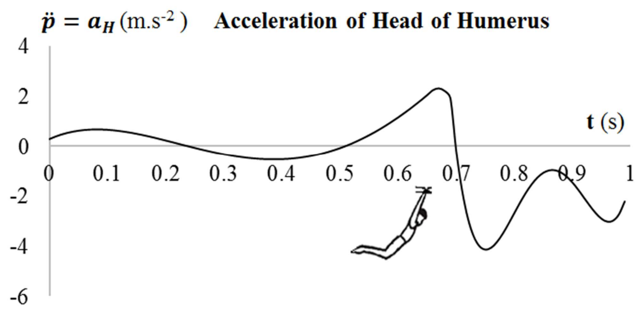

Figure 5. *Acceleration of point H with respect to point S (C7).*

The Execution errors occurred for BP movement due to the incomplete force applications of VEGH and parallel bars (by hands) (Table 2). In addition, the angle of the head and neck segment plays a critical role to minimize execution errors. Especially, the player at the right bottom of the motion (at 0.72s) μ should be zero while the body will move upward with respect to C7 (-2.88 m.s^{-2} for 58 kg), otherwise, the body will initiate the early rotation.

Table 2. *Factors effected on BP element on PB. Evaluation completed based on deductions: 0.0p, 0.3p, and 0.5p [6] of four BP elements.* $\ddot{p}$ *is maximum at t=0.68s and 0.67s; Gymnast passes the vertical position at 0.71s and 0.72s each of BP performance (*A_i *where i represents attempt).*

Factors Effect on Deduction	**Deduction of each of attempts**							
	A_1: 0.0p		**A_2: 0.1p**		**A_3:0.3p**		**A_4:0.5p**	
	0.68 s	**0.72 s**	**0.68s**	**0.72 s**	**0.67 s**	**0.71 s**	**0.67 s**	**0.72 s**
p (m)	0.025	0.035	0.026	0.035	0.026	0.036	0.025	0.034
$\ddot{p}$ (m.s^{-2})	2.20	-2.88	2.18	-2.86	1.84	-1.92	1.80	-1.88
τ_S (N.m)	5.43	7.60	5.45	7.64	5.73	7.89	5.87	8.02
R (N)	44.8	194.5	44.9	196.3	105.1	218.0	107.2	230.2
Gain Elastic Energy of Parallel Bars (J)	-	122.75	-	122.12	-	114.98	-	112.3
Angle of Head and Neck with Vertical Axis (μ)	~0^0		0^0-5^0		5^0		12^0	

Hence, the player could not gain the optimum elastic energy (122.75 J, 129.65 J for 58 kg and 60.3 kg) from the wooden bars and metal posts. For that reason, execution errors have occurred due to the lack of extension of the body at horizontal regrasping and uncontrolled regrasping after the saltos of BP.

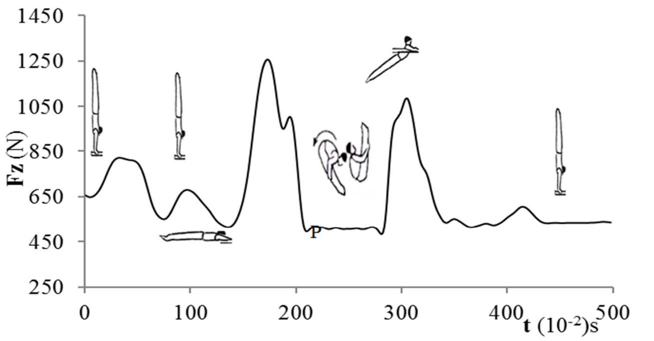

Figure 6. *Dynamic Force (Z-component) Variation of the Middle Point O of the Parallel Bars for the BP. Gymnast prepare body to starts the fall dawn from the stable handstand position in the period of 0-1.02s.*

The Giant swing backward to handstand or with inlocation forward elements are key prerequisite elements to study the Belle type elements. Currently, Coaches in China believe that if a gymnast can perform five or more repetitions of Giant circles at the same place on the parallel bars, he is ready to start to learn Belle-type elements. Hence, a gymnast can earn the right amount of elastic energy from PB to perform Giant circles in the same position of the PB without any execution errors. The next step was familiarization of the double back saltos (piked) at the right end of the PB to the mat (as a dismount). Same time gymnast, it performed on the trampoline, tumbling floor, and the floor exercise apparatus. The last progression element is BP with cable support at the middle of the bars. Gradually players will learn the Belle (tuked) element as a prerequisite element of BP. Hence, the players were acceptable to study the BP element considering the aforementioned special movement pattern (table 2) of the body segments.

4. Conclusion

The 3D biomechanical model of the VEGH joint on the parallel bars demonstrates the role of elastic properties of the shoulder joint and parallel bars interact with highly executed long swing gymnastic movements (BP). Especially, the stiffness coefficient of the shoulder joints ($K_{S,Avg}$=31,670 N.m^{-1}), the reaction on the Humeral head ($R_{S,Avg}$=196.14 N) under the bars, the direction of acceleration of the Humeral head (-2.88 m.s^{-1} implied that the player moves the body upward), the range of muscle torque around the shoulder joint (-10.8 N.m < τ_S < + 18.2 N.m), and gain the optimum elastic energy of parallel bars (122.75 J for 58 kg player) were significant factors to perform highly executed BP element (zero deduction) in China. Therefore, the VEGH joint and movements of the Head neck body segment have to consider perform highly executed BP movement on the parallel bars.

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References

[1] Arampatizis A, Bruggemann P. A mathematical high bar-human body model for analyzing and interpreting mechanical-energetic processes on the high bar. *Journal of biomechanics*. 1998; 31: 1083-1092. doi: 10.1016/s0021-9290(98)00134-1.

[2] Chandana AW, Wangang L. The Model of Shoulder Joint of Gymnast Interact with the Long Swing Gymnastic Element on the Parallel Bars. In: ISBS; 2020: 336-339. https://commons.nmu.edu/isbs/vol38/iss1/86

[3] Chandana AW, Wangang L, Mingnong Y, Xubo W. Enhancement of Gymnastic Movements with Utilizing Strain of Parallel Bars. *Sabaragamuwa University Journal*. 2017; 16 (1): 34-40. doi: 10.4038/suslj.v16i1.7716.

[4] Chandana AW, Wangang L, Mingnong Y, and Xubo W. The Parallel Bars Movements with Strain of Bars. In: *ISBS Proceedings Archive: Vol. 35 : Iss. 1*. ISBS; 2017: 113-116. https://commons.nmu.edu/isbs/vol35/iss1/29

[5] Dodig M. Model and Modelling of Dynamic Moments of Inertia of Human Body. *International Journal of Sports Science*. 2016; 6 (6): 247-256. doi: 10.5923/j.sports.20160606.08.

[6] Federation of International Gymnastics. *Code of Point: Men's Artistic Gymnastics*.; 2020.

[7] Federation of International Gymnastics. *FIG Apparatus Norms*. FIG; 2021.

[8] Hiley M, Yeadon MR. Optimum technique for generating angular momentum in accelerated backward giant circles prior to a dismount. *Journal of Applied Biomechanics*. 2003; 19: 119-130. doi: 10.1123/jab.19.2.119.

[9] Hiley MJ, Yeadon MR. Investigating optimal technique in a noisy environment: application to the upstart on uneven bars. *Hum Mov Sci*. 2013; 32 (1): 181-191. doi: 10.1016/j.humov.2012.11.004.

[10] Hiley M, Yeadon MR. The margin for errors when releasing the high bar for dismounts. *Journal of Biomechanics*. 2003; 36: 313-319. doi: 10.1016/s0021-9290(02)00431-1.

[11] Hiley M, R, Fed, Yeadon, M. the effect of cost function on optimum technique of the under somersault on parallel bars. *Journal of applied biomechanics*. Published online 2012. doi: 10.1123/jab.28.1.10.

[12] Huanbin Z, Jianshe L. *Sport Biomechanics*. Higher Education Press; 2008.

[13] Robertson G D, Hamill J, Kamen G, Whittesey NS. *Research Methods in Biomechanics*. Human Kinetics; 2013.

[14] Yeadon MR. Comparing different approaches for determining joint torque parameters from isovelocity dynamotometer measurements. *Journal of Biomechanics*. 2011; 44: 955-961. doi: 10.1016/j.jbiomech.2010.11.024.

[15] Yeadon MR, Hiley MJ. The mechanics of the backward giant circle on the high bar. *Hum Mov Sci*. 2000; 19 (2): 153-173. doi: 10.1016/s0167-9457(00)00008-7.

[16] Linge S, Hallingstad O, Solberg F. Modelling the parallel bars in Men's Artistic Gymnastics. *Hum Mov Sci*. 2006; 25 (2): 221-237. doi: 10.1016/j.humov.2005.11.008.