# THE NOVEL BIOMECHANICAL MEASUREMENT AND ANALYSIS SYSTEM FOR TUG-OF-WAR

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Tug of war (TOW) is a kind of sport that has been accepted as one of the formal items in the Olympic game. Because of having well defined rule, the TOW has high potential to be extended to all over the world in the near future. To increase the possibility of success in the competition, athletes of the TOW should be subjected to a series of training courses. After experiencing certain training course, an athlete of TOW required to carry out pulling force test to evaluate his performance and consequently verify the effectiveness of the training course. In this study, a multi-purposes biomechanical measurement and analysis system is proposed in which various evaluations of the athlete performance. The idea of the proposed system is discussed and the associated theoretical methods are derived.

**KEY WORDS:** training, sports biomechanics

**INTRODUCTION:** There are many studies concerning the strategy of how to increase the probability of success in the TOW (Tu, 2005). Wong (2002) used a neural network to model the force pattern when the members of the team rise up in turn after sitting on the floor. In this study, many works have been accomplished. Firstly, they quantified kinematics variables of body segment positions and body segment angles during a live competitive pull; Secondly, they quantified and contrasted the variables measured for technically proficient teams on attack with those of technically inefficient teams on defines for each competitive class observed. Finally, they quantify and contrast variations in the variables measured for different pulling positions on the rope during attack and defence.
All these previous works have achieved excellent results for their cases. However, study on development of performance evaluation systems for individual athlete of the TOW is very limited. To increase the possibility of success in the competition, athletes of the TOW should be subjected to a series of training courses. After experiencing certain training course, an athlete of TOW required to carry out pulling force test to evaluate his performance and consequently verify the effectiveness of the training course. This paper proposes a multi-purposes biomechanical measurement and analysis system (BMAS) in which various evaluations of the athlete performance. Exclude the actual human experimental operation and data integration related issues. The proposed system was focus on the theoretical method derived.

**METHODS and RESULTS: 1.System configuration:**The configuration of the biomechanical measurement and analysis system BMAS is shown in Figure 1. The designed system is mainly consisted of a digitizing system for collecting body segment parameters; a synchronizer to synchronize the starts of pulling action (through an infrared-emitting diode (LED), photo capturing, and force data recording; a pulling force estimation module to estimate true pulling force using the force sensor data; the joint moment analysis module for calculating all the joint moments of body; and finally the force curve analysis module based on our previous work (Tu, 2005) to characterize the performance of the athlete. The force sensor installed between the rope and the wall through a steel chain is of dynamic type which is capable of measuring dynamic pulling force. The measured force signal is amplified through a electronic amplifier and filtered through a digital filter before recorded.

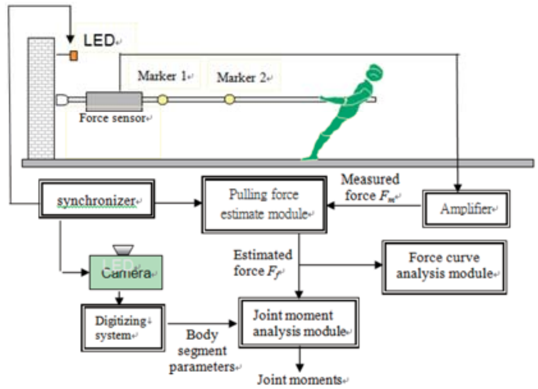



**Figure 1: Schematic diagram of systemthe proposed BMAS**

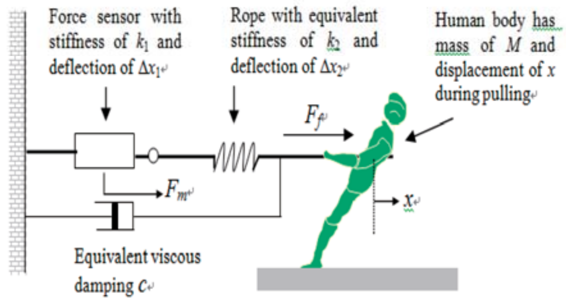



**Figure 2: Model of the rope-human during pulling**

**2.Pulling force estimation:** To evaluate the performance of an athlete of TOW, dynamic pulling force exerted by the athlete is measured and analyzed. It is usually performed by letting the athlete pulls a force sensor via the rope to measure his pulling force, Ff , as shown in Fig.2. During the test, it is well known from dynamic theory that the condition Ff =Fm only holds in steady state. However, because of the non-rigidity of the rope-sensor system, it is not the case in transient state. That is to say, the force reading of the force sensor in the test may not truly represent the actual applying force of the athlete. Thus problems arise in the measurement: what is the relationship between Ff and Fm, and how to estimate Ff from Fm. To clarify this question, a rope-human system is proposed as shown in Fig.2. In the rope-human system, $M$ is the mass of the athlete, $k_1$ is the stiffness of the strain gauge of the force sensor, $k_2$ is the equivalent stiffness consists of that the rope, human structure, and the shoe of the athlete, and $F_f$ is the pull force exerted by the athlete. Express the equivalent stiffness of the system as(1), The dynamic model of system can be modeled as (2):

$$\frac{1}{k_0} = \frac{1}{k_1} + \frac{1}{k2} \rightarrow k_0 = \frac{k_1 k_2}{k_1 + k_2} \quad (1) \qquad m\ddot{x} + c\dot{x} + k_0 x = F_f \quad (2)$$

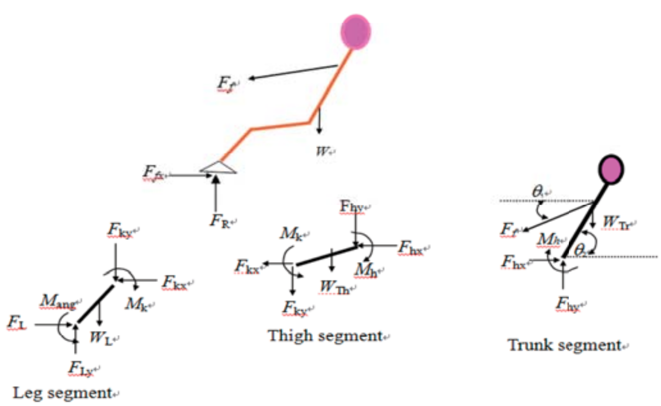
Here, $x$ is moving distance of the human body and has the relation of $x = \Delta x_1 + \Delta x_2$, with $\Delta x_1$ and $\Delta x_2$ being the deflections of the springs $k_1$ and $k_2$, respectively.Due to the fact of

$$k_1 \Delta x_1 = k_2 \Delta x_2 \text{, i.e.} \rightarrow \Delta x_2 = \frac{k_2}{k_1}\Delta x_1 . \rightarrow k_1 x = k_1 \Delta x_1 (\frac{k_1 + k_2}{k_2}) \quad (3)$$

Multiplying both sides of Eq.(2) by $k_1$, we have $mk_1\ddot{x} + ck_1\dot{x} + k_0 k_1 x = k_1 F_f$ (4). By using Eq. (3), Eq.(4) becomes $m\frac{k_1 + k_2}{k_2} k_1 \Delta\ddot{x}_1 + ck_1 \frac{k_1 + k_2}{k_2}\Delta\dot{x}_1 + k_o k_1 (\frac{k_1 + k_2}{k_2})\Delta x_1 = k_1 F_f$ (5).

Since the pulling force measured by the strain gauge is $F_m = k_1 \Delta x_1$, Eq.(4) becomes: $\ddot{f}_m + \frac{c}{m}\dot{f}_m + \frac{k_0}{m} f_m = \frac{k_o}{m} F_f$ (6). Let $\omega_n = \sqrt{\frac{k_0}{m}}$ and $2\xi\omega_n = \frac{c}{m}$ . It follows that $\ddot{f}_m + 2\xi\omega_n \dot{f}_m + \omega_n{}^2 f_m = \omega_n{}^2 F_f$ (7). Were $\omega_n$ and $\xi$ are the nature frequency and damping ration of the system, respectively. Equation (7) in Laplace form is $f_m = \frac{\omega_n{}^2}{s^2 + 2\xi\omega_n s + \omega_n{}^2} F_f$ (8). where *s* is the Laplace variable. With Equation (8) at hand, the relation between $F_m$ and $F_f$ can be illustrated by Fig.3. The human–rope system forms a vibration system with its vibration frequency dominated by the stiffness of the rope. Transfer function between $F_m$ and $F_f$ in Eq.(8) shows that $F_f$ will induce a vibratory response of $F_m$ to a certain extent, since $F_f$ is of impulsive force in nature. Depending on the value of the rope stiffness, the response of $F_m$ corresponding to the same pattern of $F_f$ is quite different. A small value of rope stiffness will result in a low frequency vibratory $F_m$ pattern. In physical words, when an abrupt pulling force is applied to the rope, a low frequency vibration will be excited in the system. As a result, a vibratory of $F_m$ pattern is generated and consequently $F_f \neq F_m$ in the transient state. On the other hand, if the value of the rope stiffness is high enough, due to the low pass filter characteristics of the system, the high frequency ripple components of $F_m$ will be filtered out. Then $F_m$ can be approximately assumed to equal to $F_f$, that is $F_f \cong F_m$. However, because of the non-rigidity nature of the rope system, $F_m$ should never be assumed to be equal to $F_f$ in practical applications, if the accuracy is highlighted in the analysis.

**3.Force curve analysis:** From Eq.(7), if the system parameters $\omega_n$ and $\xi$ are known a prior, the actual applied force $F_f$ can be obtained from the measured time series of $f_m$. The parameters $\omega_n$ and $\xi$ can be determined form the vibratory pattern of $f_m$. When the system is subjected to an impulsive force of $F_f$, the vibratory part of $f_m$ is shown in Fig. 4. From this figure, the damped natural frequency $\omega_d = 2\pi/\tau_d$ and logarithmic decrement $\delta = \ln(A_1/A_2)$ can be calculated. Then, the natural frequency($\omega_n$) and damping ratio ($\xi$) of the system can be obtained as: $\xi = \frac{\delta}{\sqrt{(2\pi)^2 + \delta^2}}$ and $\omega_n = \frac{\omega_d}{\sqrt{1-\xi^2}}$ (9).



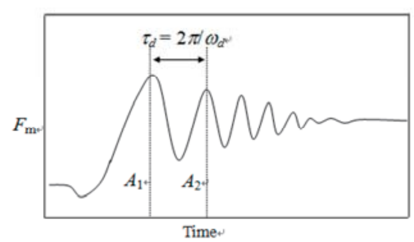




**Figure3:**Body segment free body diagram **Figure4:**Calculations of $\omega_d$ and $\tau_d$ from the response of $F_m$

Here, we notice that if $A_1$ and $A_2$ are closed in value that experimental distinction between them is impractical, the above analysis should be modified by using two observed amplitudes that are *n* cycles apart(Figure4).

**4.Joint moment calculations:** The model for this purpose comprised 3 rigid segments: trunk, thigh, and leg segments, as shown in Fig.3. Taking each segment as a separated free body and assuming that the center of gravity of each segment is located at its center, the joint moments $M_k$, $M_h$ and $M_{ang}$ can be determined from static balancing equations as follows.

**Trunk segment.** Since the pulling force ($F_f$), the trunk weight ($W_{Tr}$), trunk length ($l_{Tr}$), and the angles ($\theta_1$ and $\theta_2$ ) are measurable, the trunk joint moment ($M_h$) as well as the reaction forces ($F_{hy}$ and $F_{hy}$) are determined using the following equations:

$M_h$ =(2/3) $F_f l_{Tr}\cos(\theta_1)\sin(\theta_2)$-(1/2)$W_{Tr}$ $l_{Tr}\cos(\theta_2)$- (2/3)$F_f l_T r\sin(\theta_1)\cos(\theta_2)$

$F_{hy}= F_f \sin(\theta_1)+W_{Tr}$ $\rightarrow$ $F_{hx}= F_f\cos(\theta_1)$ (9)

**Thigh segment.** With the same manner as the trunk segment, the knee joint moment ($M_k$) and the accompanied reaction forces ($F_{kx}$, $F_{ky}$) are calculated as follows.

$M_k = F_{hy} l_{Th}\cos(\theta_3)-F_{hx} l_{Th}\sin(\theta_3)+M_h+(1/2)W_{Th} l_{Th}\cos(\theta_3)$

$F_{kx}= F_{hx}$ $\rightarrow$ $F_{ky}= F_{hy} +W_{Th}$ (10)

**Leg segment.** Similarly, the ankle joint moment ($M_{ang}$) and the reaction forces ($F_{Lx}$, $F_{Ly}$) are determined as:

$M_{ang} = F_{ky} l_L\cos(\theta_4)-F_{kx} l_L\sin(\theta_4)+M_k+(1/2)W_L l_L\cos(\theta_4)$

$F_{Lx}= F_{hx}$ $\rightarrow$ $F_{Ly}= F_{hy} +W_L$ (11)

After rearranging the above equations (10)-(12), the three joint moments are obtained as:

$M_h$ =(2/3) $F_f l_{Tr}\cos(\theta_1)\sin(\theta_2)$-(1/2)$W_{Tr}$ $l_{Tr}\cos(\theta_2)$- (2/3) $F_f l_{Tr}\sin(\theta_1)\cos(\theta_2)$

$M_k = [F_f\sin(\theta_1)+W_{Tr}]\, l_{Th}\cos(\theta_3)-[F_f\cos(\theta_1)]\, l_{Th}\sin(\theta_3) + M_h + (1/2)W_{Th} l_{Th}\cos(\theta_3)$

$M_{ang} = (F_f\sin(\theta_1)+W_{Th} +W_{Tr})\, l_L\cos(\theta_4) - [F_f\cos(\theta_1)]\, l_L\sin(\theta_4)+M_k+(1/2)W_L l_L\cos(\theta_4)$ (12)

With these equations, the joint moments corresponding to specific values of pulling force ($F_f$) can be easily calculated by using numerical simulations.

**CONCLUSION:** In the present paper, theoretical methods for pulling force estimation and joint moment analysis modules have been derived. Experimental verification for the proposed system is being carried out and will be presented in the near future.

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