Determination of Tenpin Bowling Lane's Rolling Resistance Based on Kinetics and Kinematics Modeling

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Abstract Bowling alleys have significant influence on tenpin bowler's performance. The lane surface is one of the major factors in determining the player's results in a bowling tournament due to the ball–lane surface interaction. Understanding on how to adapt to different lane conditions will help bowlers to perform better. This study investigates rolling resistance coefficients of bowling ball–lane surface based on kinetics and kinematics modeling approach. Ball throwing phase was modeled where the bowler's throwing arm is defined as one rigid single connecting rod on a pivoted joint of the shoulder. Power generated from the throw is derived based on the work done by the arm during the throwing time interval. The amount of work done by the throwing arm is derived from the amount of torque generated from the throw during the throwing time interval. The rolling resistance coefficient of the thrown ball was calculated based on the power required to make the ball roll on the lane. Modeling results identify ball release velocity, ball velocity, and throwing arm angular velocity as parameters that are capable of being manipulated by the bowler in order to obtain desired throwing power. This, however, depends on the ball–lane rolling resistance coefficient and the ball's drag coefficient. Modeling information should enable bowlers to adjust their throwing mechanics to adapt with bowling lane conditions.

Keywords Tenpin bowling · Modeling · Rolling resistance · Kinematics and kinetics

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1 Introduction

Tenpin bowling is a sport that combines speed, velocity, momentum, accuracy, and consistency. These elements relate with many other aspects, including the bowler's physical and mental strength, the ball used, lane conditions, and throwing technique.

Almost every time, lane conditions are the only aspects that bowlers have no control. The lane conditions are determined by the maintenance techniques performed by the bowling alley operators. Professional bowlers should be able to adjust their throwing technique when playing at a bowling alley that has different lane conditions compared to the one that the bowlers are already accustomed to, in terms of the lane surface conditions and also air circulation pattern near the bowling lane.

However, when one or two pin count differences determine winners and losers, these adjustment periods will be critical. Bowlers do not have empirical data and statistical data that show how the lane conditions on that particular day will affect their normal playing technique and plan. They will just adjust their throwing speed and technique to accommodate to the required adjustment. Information that explains about the lane conditions benefits bowlers in reducing the time of the adjustment period.

The physics of throwing can be understood either experimentally or numerically. Modeling has always been used at the beginning of an experimental based research. This is to provide guidelines for the researchers before embarking into the experimental phase. The modeling of throwing usually focuses on the related segmental body parts rather than the whole body movement model [1]. Limb-segment angles, joint angles, and velocities (linear and angular) are typically investigated to develop a throwing model [1, 2].

A previous study showed that typical angular velocity of the bowler's throwing hand is around 617 °/s [3]. This covers the arm's maximal hyperextension to flexion phase until the ball release time. In terms of ball release velocity, a previous study had indicated that for elite player the average ball release velocity was in the order of 28.4 km/h, whereas for semi-elite players, the average ball release velocity was 27.2 km/h [4]. Similar results were also found in another study [5]. It was also reported that the typical average ball velocity that travels toward the pin ranges between 22 and 26 km/h [6]. In terms of rolling resistance and drag force that associate the bowling ball with the bowling lane and bowling alley, there were no clear past studies that focused on tenpin bowling. However, it is understood that typical drag coefficient for sports ball with smooth surface that travels at relatively moderate to high velocity is below 0.3 [7, 8], and the coefficient of rolling resistance between two smooth surfaces with lubrication influence will be around 0.02–0.1 [9].

The present study focuses on identifying a simple model of bowling throw. After identifying this model, the rolling resistance between the ball and the lane will be estimated. Information regarding the lane's rolling resistance is important to help bowlers to understand better about lane conditions.

2 Method

2.1 Mathematical Modeling

The modeling of the throwing phase is performed as if the arm is one rigid single connecting rod on a pivoted joint of the shoulder. Power generated from the throw is derived based on the work done by the arm during the throwing time interval. The amount of work done by the throwing arm is derived from the amount of torque generated from the throw during the throwing time interval. This is shown in the equation below.

Power requirement to throw the ball:

$$P = \frac{W}{t}, \tag{1}$$

where W is the work done and t is the time used to perform the task. The work done during the throwing phase is defined by the following equation.

Work done during the throwing phase:

$$W = \int \tau \mathrm{d}\theta = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2 \tag{2}$$

Therefore, the power required to throw the ball is:

$$P = \frac{mv^2 + I\omega^2}{2t} \tag{3}$$

where t is the torque, θ is the angle, m is ball mass, v is ball release velocity, I is moment inertia of the arm, w is angular velocity of the throwing arm, and t is time used to perform the task. Here, the amount of torque generated in performing the work is defined as the amount of linear and rotational kinetic energy of the movement.

As the arm is modeled as a single connecting rod on a pivoted joint at shoulder (Fig. 1), the moment of inertia of the throwing arm can be modeled as shown in the equation below:

$$I = \frac{1}{12}ML^2 + Mr^2 \tag{4}$$

Here, M is arm mass, L is the arm length, and r is the arm distance between arm's center of mass to the shoulder pivot joint. Here, we consider that the arm's mass is equally distributed.

The power generated by the throwing arm is also equal to the force that is required to roll the ball on the lane and the drag force generated during the ball moving on the lane. This is illustrated in the following equation.

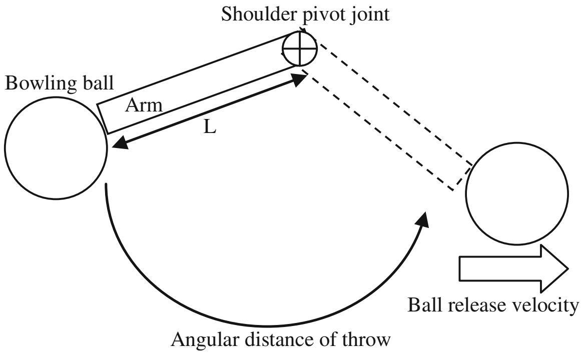


Fig. 1 Modeling of throwing arm

Power required for moving the ball on the lane:

$$P = \left(C_{\mathrm{r}} mg + \frac{1}{2}\rho_{\mathrm{a}} C_{\mathrm{d}} A V^2\right) V \tag{5}$$

where C_{r} is the rolling resistance coefficient between ball and lane, m is ball mass, g is gravity acceleration, ρ_{a} is air density surrounding the lane, C_{d} is drag coefficient between ball and air during ball movement on lane, A is ball cross-sectional area, and V is the ball velocity.

If we consider that the power that is required to throw the ball is equal to the power that is required to move the ball on the lane, the following equation will represent the rolling resistance coefficient of the ball–lane:

$$C_{\mathrm{r}} = \frac{mv^2 + I\omega^2 - \rho_{\mathrm{a}} C_{\mathrm{d}} A V^3 t}{2Vmgt} \tag{6}$$

2.2 *Modeling Parameters*

The parameters utilized in this study to calculate the model are presented in Table 1. All of the chosen values for the modeling parameters are based on typical and average quantities that were found or were used in previous studies [1, 3–9].

Based on the modeling parameters shown in Table 1, the amount of work and power required to throw the ball can be calculated. This will help to solve the next stage of the simulation model.

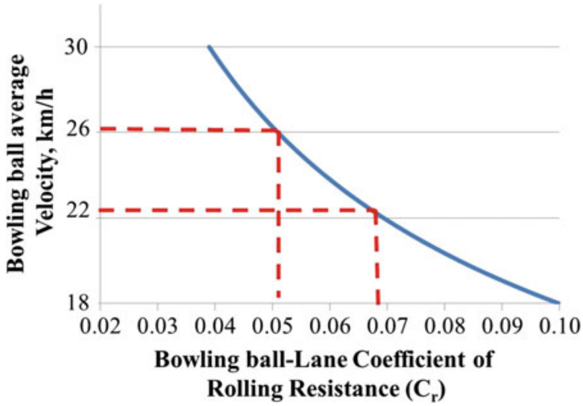
3 Results and Discussion

Figure 2 shows the modeling results of bowling ball–lane rolling resistance coefficient, C_{r}, and the bowling ball average ball speed. Based on average ball speed that travels toward the pin as reported from a previous study [6], it was

Table 1 Modeling parameters

No.	Modeling parameters	Value
1	Bowler's height	180 cm
2	Bowler's weight	80 kg
3	Bowler's arm mass	10.5 kg
4	Bowler's arm moment of inertia	1.97 kg m^2
5	Bowler's arm angular velocity	11 rad/s
6	Ball release velocity	28.4 km/h
7	Ball throwing period	2 s
8	Bowler's arm length	75 cm
9	Bowling ball mass	7 kg
10	Bowling ball diameter	21.6 cm
11	Bowling ball cross-sectional area	0.04 m^2
12	Air density at 20 °C	1.2 kg/m^3
13	Drag coefficient of bowling ball	0.1–0.3
14	Rolling resistance coefficient between ball and lane	0.02–0.1
15	Gravity acceleration	9.81 m/s^2

Fig. 2 Ball average velocity and rolling resistance coefficient (C_r)



indicated that the typical average ball speed was between 22 to 26 km/h. We can identify from the modeling results in Fig. 2 that the possible value of C_r is between 0.05 and 0.07. In this simulation, it was also found that the potential power requirement to throw the ball based on this model was 0.34 KWh.

Based on the results in Fig. 2, a relationship between the required power to throw the ball and the ball average velocity toward the pin was modeled. Figures 3, 4, and 5 represent the simulation model with drag coefficient of bowling ball C_d at 0.1, 0.2, and 0.3, respectively. In each of this simulation, the C_r was set between the ranges of 0.02–0.1. This should cover more than ±25 % of the estimated C_r based on the early modeling results.

Simulation results shown in Figs. 3, 4, and 5 indicated that C_r does not influence much the ball that travels below 10 m/s on average. It can also be seen that at

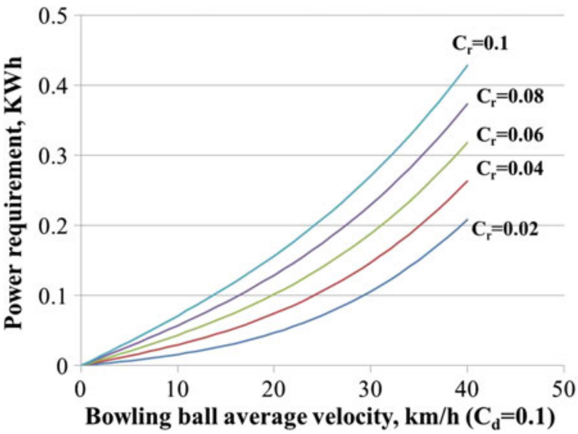


Fig. 3 Ball average velocity–power requirement ($C_d = 0.1$)

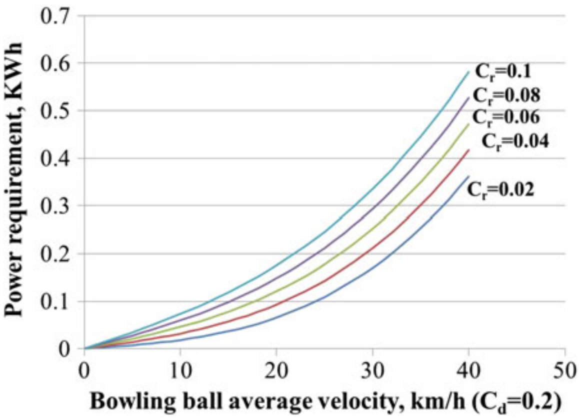
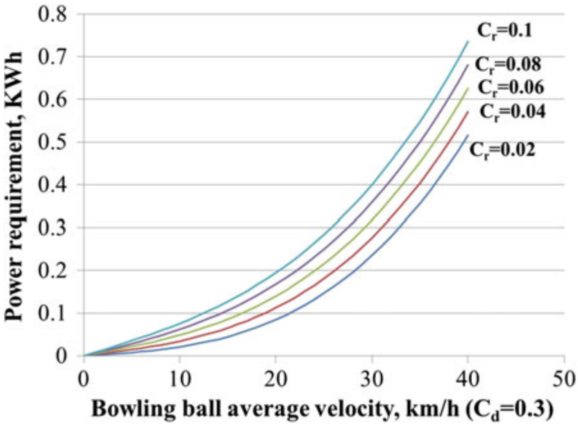


Fig. 4 Ball average velocity–power requirement ($C_d = 0.2$)

10 km/h average velocity and below, there is little influence of C_d on the power requirement. The increasing amount of C_r and C_d will proportionally increase the power requirement during throwing the ball. This is because more energy is needed to overcome the resistance generated by the increasing amount of drag and rolling resistance. Based on the average ball velocity at 22 km/h, the power required to throw the ball is in the range of 0.05–0.23 KWh.

In simulating the power required to throw a bowling ball, the ball release velocity and the arm angular velocity are utilized in the model. Therefore, in real world situations, if there are possible way to measure the ball release velocity, arm angular velocity and other basic information such as the bowler's anthropometry data, bowling ball information, and environmental aspects like the room temperature and air density, we can identify the amount of rolling resistance of the bowling lane. Based on this information, we can systematically identify the suitable average ball velocity as well as its throwing power requirement.

Fig. 5 Ball average velocity–power requirement ($C_d = 0.3$)



This real-time information will help bowlers to adjust their throwing effort in order to adapt to different bowling lane condition, especially if they are not familiar with the bowling lane surface.

4 Conclusion

This study proposed a simple model to understand the throwing ball phase of tenpin bowling. In developing this model, important aspects such as power requirements, lane's rolling resistance coefficient, and ball's drag coefficient were estimated. An understanding of the information helps bowlers to adapt faster during playing at unfamiliar bowling alleys. By reducing the adjustment time to adapt to the lane's condition, improvement on total pin score can be achieved. However, further experimental work should be carried out to validate the model. Furthermore, the arm swing model during ball throw need to be further improved.

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