SCIENTIFIC JOURNAL OF SPORT AND PERFORMANCE

ORIGINAL ARTICLE

Minimal force to move the heavier opponent: Investigation of sumo game

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ABSTRACT

In sports and daily life, we often experience situations where we should carry an object by pushing it. In this study, we analyse sumo, a Japanese traditional sport, in which one can be a winner by pushing the opponent to the outside of dohyo, the wrestling ring. The optimal strategy for the lighter wrestler to carry the heavier opponent by sliding on dohyo is explored in terms of physics. Although the lighter wrestler can never slide the opponent by pushing forward, this can be achieved by exerting the force diagonally upward. As a result of analysis, we obtain the magnitude and direction of the force that should be applied to initiate the sliding motion and ensure its fastest movement. The result reveals the existence of a critical weight ratio of the wrestlers; if the ratio is upper than a certain value, the lighter wrestler should push to a specific direction, while otherwise the optimal force direction depends on the weight. Due to the generality of physics and mathematics, the application is not limited to sumo; the result provides the most effective way to carry an object on a floor in all activities in sports, exercises, and daily life.

Keywords: Performance analysis of sport, Biomechanics, Theory, Sumo, Game analysis, Optimal strategy.

Cite this article as:
Iwasa, M. (2023). Minimal force to move the heavier opponent: Investigation of sumo game. *Scientific Journal of Sport and Performance*, *2*(2), 151-164. https://doi.org/10.55860/HSNY2515

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Submitted for publication December 02, 2022.
Accepted for publication January 18, 2023.
Published January 28, 2023.
Scientific Journal of Sport and Performance. ISSN 2794-0586.

doi: https://doi.org/10.55860/HSNY2515

INTRODUCTION

In sports as well as daily life, we often have to carry a heavy object by sliding on a floor. Then, we can have a question: what is the most effective way to achieve it? How strongly and in which direction should we push the object? We find such a situation typically in sumo, a Japanese traditional sport. In the game of sumo, two wrestlers fight inside of a 4.55 m circle on a clay platform, namely, *dohyo*. If a wrestler steps outside of the circle, the wrestler is declared the loser. Therefore, one of the ways to be a winner is to push the opponent strongly, make the opponent slide on the *dohyo*, and successfully push the opponent out of the circle. In this study, by applying the laws of physics, we explore the force required to make the opponent slide.

In general, to slide an object on a plane surface, we must apply a force that exceeds the friction between the object and the surface. Regarding friction, it is known that the maximum friction force arising in a static object, referred to as the limiting static friction F_0, is proportional to the force perpendicular to the plane, referred to as the normal force N , that is, $F_0 = \mu_s N$, where the proportionality constant μ_s is referred to as the static friction coefficient (Halliday et al., 2013).

Assume two sumo wrestlers, A and B, have a bout, and A is lighter than B. Then, as evident in the following image, the lighter wrestler A cannot make the heavier opponent B slide if A simply pushes B forward.

The weights of A and B are set to w and W, respectively. Since A is lighter than B, they satisfy $w < \mathrm{W}$. With regards the forces in the vertical direction, the weights on A and B are, respectively, balanced with the normal forces applied by *dohyo*, N_A, and N_B, i.e., $N_A = w$ and $N_B = W$. Hence, their limiting static frictions, F_{0A} and F_{0B}, are given by $F_{0A} = \mu_s w$ and $F_{0A} = \mu_s W$, and therefore $F_{0A} < F_{0B}$ is satisfied, indicating that the limiting static frictions for A is smaller than that for B.

If A pushes B horizontally with a force of the magnitude f (Figure 1a), according tothe Newton's third law, namely, the action-reaction law, A is simultaneously pushed by B with an equal and opposite force (Halliday et al., 2013). Therefore, while A increases the force magnitude f, f exceeds F_{0A} before f exceeds F_{0B}, which indicates that A must begin to slide on *dohyo* before B begins to slide.

However, if A pushes B diagonally upward (Figure 1b), as described in the following sections, it is possible that the limiting static force of A becomes larger than that of B because the normal force on B reduces while that on A increases, and therefore there is a possibility that A can make B slide without sliding backward.

In this study, we investigate the settings under which a lighter wrestler can push a heavier wrestler; in other words, how a light wrestler can strategically push a heavier opponent in a sumo game. Due to the advantage in generality of physics and mathematics, the result would be able to be applied not only to sumo games but also to other various situations in sports as well as in life in carrying a heavy object on a floor. Note that, to avoid the complexity of the discussion, the rotation of the wrestler's body is out of the scope of this study. The rotational motion can be separated from the sliding motion in terms of mechanics and would be independently investigated in another study.

MATERIAL AND METHODS

Model

We consider a situation in which the lighter wrestler A pushes the heavier wrestler B diagonally upward. We set the vertical and horizontal component of the force to be $f_\perp$ and $f_\parallel$, respectively (Figure 1b).

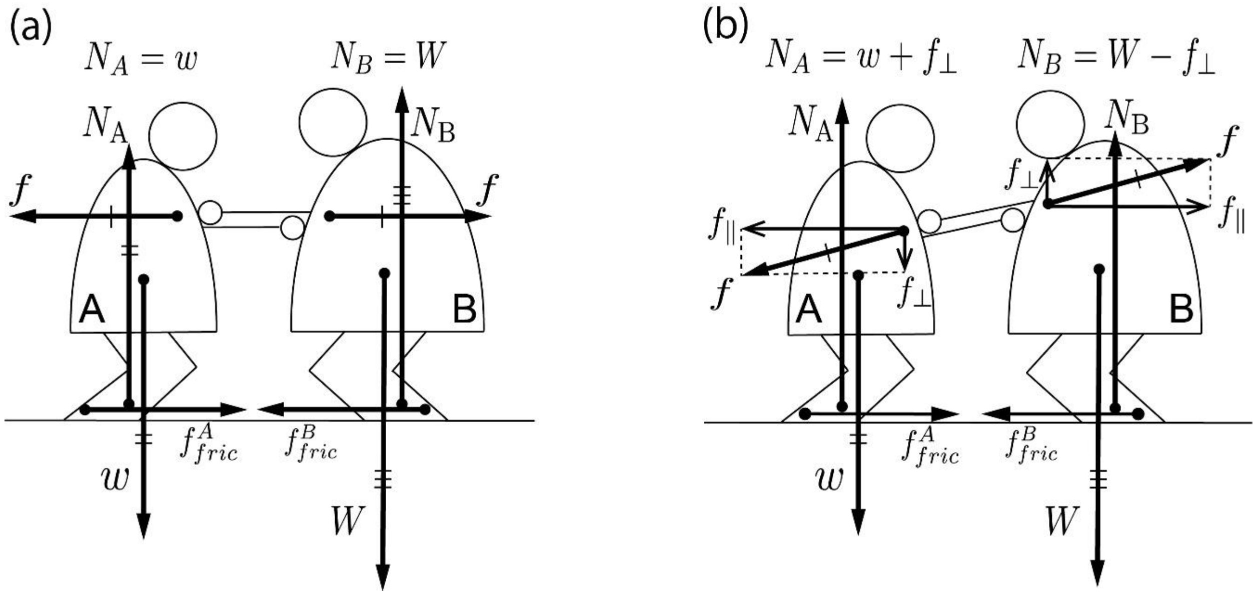

Figure 1. Forces exerted upon the two wrestlers in sumo when the lighter wrestler A pushes the heavier opponent B with a force magnitude f. (a) Case in which A pushes B in the horizontal direction. (b) Case in which A pushes B in a diagonally upward direction.

According to the action-reaction law, the reaction force is generated diagonally downward. Because the magnitude of the vertical component of the reaction force is also $f_\perp$, the normal forces on A and B are:

$$N_A = w + f_\perp, \quad (1)$$
$$N_B = W - f_\perp, \quad (2)$$

which comes from the force balances on A and B in the vertical direction. Therefore, the condition that A can make B slide without sliding backward, namely $F_{0A}(= \mu_s N_A) > F_{0B}(= \mu_s N_B)$ for the limiting static friction, is given by:

$$\mu_s(w + f_\perp) > \mu_s(W - f_\perp), \quad (3)$$

which leads to:

$$f_\perp > \frac{W - w}{2} \quad (4)$$

For A to slide B, another condition must be satisfied; it is necessary that the horizontal component of the force applied to B, $f_\parallel$, exceeds the limiting static friction, $F_{0B}(= \mu_s N_B)$. In other words, according to (2), the relation,

$$f_\parallel > \mu_s(W - f_\perp), \quad (5)$$

must be satisfied.

Thus, the conditions under which the lighter wrestler A can make the heavier opponent B slide are given by the inequalities, (4) and (5). Figure 2a and 2b depicts the region satisfying the relations (4) and (5). If A pushes B with the force represented by points in the shaded region in those figures, B begins to slide without A sliding backward.

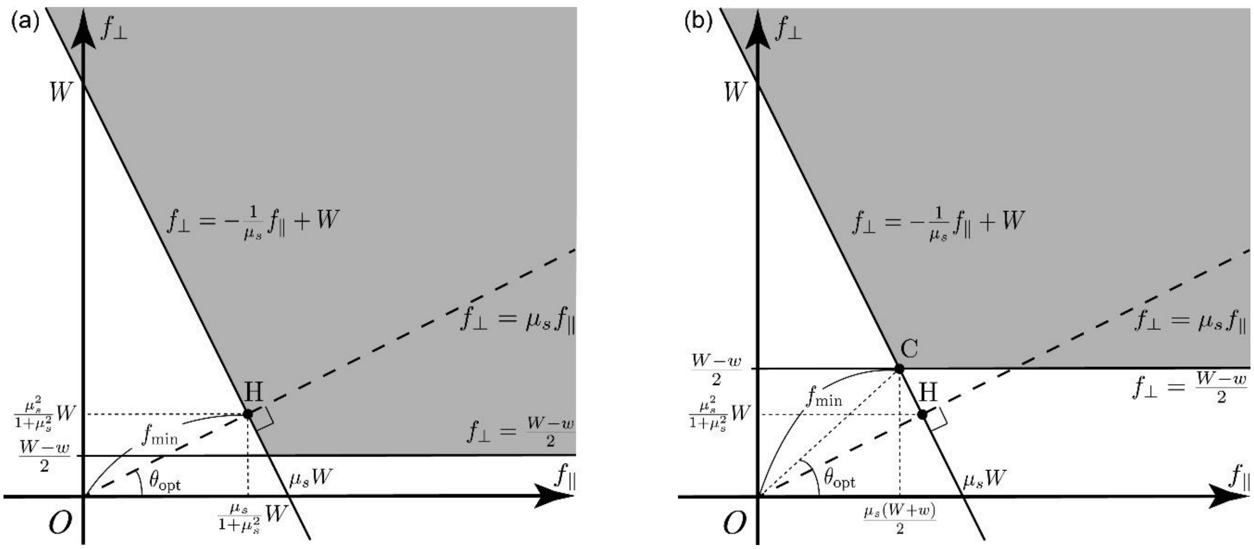

Figure 2. The range in which the lighter sumo wrestler A can make the heavier opponent B slide without sliding backward. (a) When the lighter wrestler is sufficiently heavy ($w \geq \frac{1-\mu_s^2}{1+\mu_s^2} W$), the minimal force required to slide B is represented by point H. (b) When the lighter wrestler is not sufficiently heavy ($w < \frac{1-\mu_s^2}{1+\mu_s^2} W$), the minimal force required to slide B is represented by point C.

RESULTS

Minimal force for sliding

Let us find the minimum magnitude of force, $f_{\min}$, required for A to slide B. Let the angle between the horizon and the force direction be θ_{opt} when the force is exerted. The minimal force is graphically represented by the point whose distance from the origin has the minimum value in the shaded region in Figure 2. Then, there are qualitatively different two cases corresponding to Figure 2a and Figure 2b.

In the first case (Figure 2a), the point H, the foot perpendicular from the origin to the line $f_\parallel = \mu_s(W - f_\perp)$, that is,

$$f_\perp = -\frac{1}{\mu_s} f_\parallel + W, \qquad (6)$$

is included in the boundary of the shaded region. In this case, the force corresponding to H is the minimal force. In the second case (Figure 2b), the point H is not included in the boundary of the shaded region. In this case, the force represented by the point C is the minimal force.

Let us analyse the first case. Because the line perpendicular to the line (6) and passing through the origin is represented by:

$$f_{\perp} = \mu_s f_{\parallel}, \tag{7}$$

the coordinates of H are:

$$f_{\perp} = \frac{\mu_s^2}{1+\mu_s^2} W, \tag{8}$$
$$f_{\parallel} = \frac{\mu_s}{1+\mu_s^2} W \tag{9}$$

Therefore, point H is located on the boundary of the shaded region in Figure 2 (i.e., the first case occurs) when:

$$\frac{\mu_s^2}{1+\mu_s^2} W \geq \frac{W-w}{2}, \tag{10}$$

in other words, when the ratio of the weights satisfies:

$$\frac{w}{W} \geq \frac{1-\mu_s^2}{1+\mu_s^2} \tag{11}$$

In this case, the force H in Figure 2a is the minimal force. Then, its magnitude $f_{\min}$ is given by:

$$\begin{aligned} f_{\min} &= \sqrt{f_{\perp}^2 + f_{\parallel}^2} \\ &= \frac{\mu_s}{\sqrt{1+\mu_s^2}} W \end{aligned} \tag{12}$$

The direction of the force is given by θ_{opt} in Figure 2a, which is determined from the relation,

$$\begin{aligned} \tan\theta_{\text{opt}} &= \frac{f_{\perp}}{f_{\parallel}} \\ &= \mu_s \end{aligned} \tag{13}$$

Let us analyse the second case, in which the condition (11) is not satisfied, i.e.:

$$\frac{w}{W} < \frac{1-\mu_s^2}{1+\mu_s^2} \tag{14}$$

Then, the minimal force is represented by point C in Figure 2b, which is the intersection of the line (6) and the line:

$$f_{\perp} = \frac{W-w}{2} \tag{15}$$

By substituting Equation (15) into Equation (6), we obtain:

$$f_{\parallel} = \frac{\mu_s(W+w)}{2} \quad (16)$$

at point C. Hence, the magnitude of the minimal force f_{min} is given by:

$$\begin{aligned} f_{\text{min}} &= \sqrt{f_{\perp}^2 + f_{\parallel}^2} \\ &= \frac{\sqrt{(1-\frac{w}{W})^2 + \mu_s^2(1+\frac{w}{W})^2}}{2} W \end{aligned} \quad (17)$$

The direction of the force is given by the angle θ_{opt} in Figure 2b, which is deter- mined from:

$$\begin{aligned} \tan\theta_{\text{opt}} &= \frac{f_{\perp}}{f_{\parallel}} \\ &= \frac{W-w}{\mu_s(W+w)} \end{aligned} \quad (18)$$

Range of the force direction

Assuming that the lighter wrestler A can produce a strong force f_0 that sufficiently exceeds f_{min}, let us find the force direction in which A can make the heavier opponent B slide.

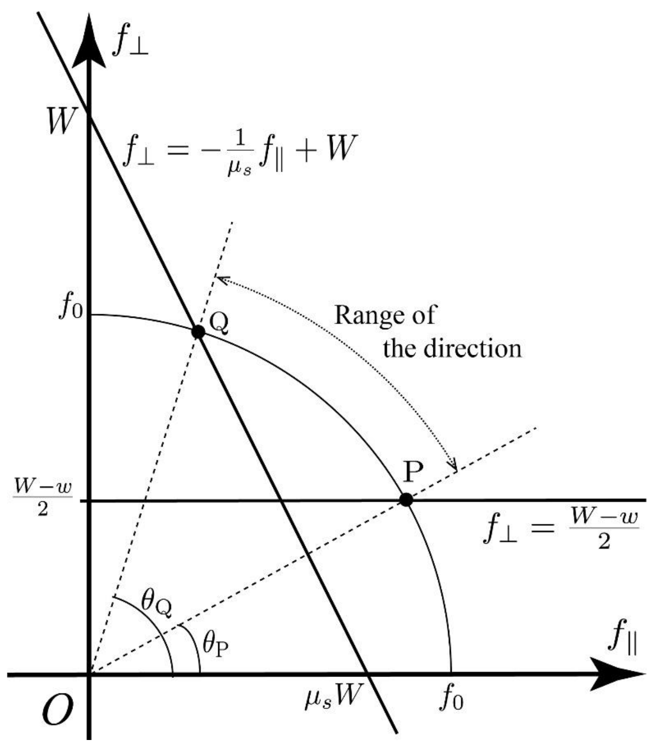

Figure 3. The range of the force direction in which the lighter wrestler can make the heavier opponent slide when the lighter wrestler pushes with a force of magnitude f_0 that exceeds f_{min}

The direction range is represented by $\theta_P < \theta < \theta_Q$ in Figure 3. Point P is the intersection of the line (15) and a circle with centre at the origin and radius f_0. Point Q is the intersection of the line (6) and the same circle. When A pushes in a direction in this range, it is possible to slide B without sliding backward.

Let us calculate θ_P and θ_Q. At the point P, since:

$$f_0 \sin\theta_{\mathrm{P}} = \frac{W - w}{2} \tag{19}$$

holds according to Equation (15), θ_P is given by:

$$\theta_{\mathrm{P}} = \arcsin\frac{W - w}{2f_0} \tag{20}$$

At the point Q,

$$f_0 \sin\theta_{\mathrm{Q}} = -\frac{1}{\mu_s} f_0 \cos\theta_Q + W \tag{21}$$

holds according to Equation (6). By transforming Equation (21), we obtain:

$$\cos(\theta_{\mathrm{Q}} - \phi) = \frac{\mu_s W}{\sqrt{1 + \mu_s^2} f_0}, \tag{22}$$

where ϕ is defined by $\tan\phi = \mu_s$, which corresponds to θ_{opt} in Figure 2a. Therefore, θ_{Q} is given by:

$$\theta_{\mathrm{Q}} = \arctan \mu_s + \arccos\left(\frac{\mu_s W}{\sqrt{1 + \mu_s^2} f_0}\right) \tag{23}$$

In summary, when the lighter wrestler A pushes the heavier opponent B with a sufficiently large force of magnitude f_0 [1] exceeding f_{min}, B starts sliding before A slides backward if A pushes B in the direction of:

$$\arcsin\left(\frac{W - w}{2f_0}\right) < \theta < \arctan \mu_s + \arccos\left(\frac{\mu_s W}{\sqrt{1 + \mu_s^2} f_0}\right) \tag{24}$$

Optimal force direction

To end the bout swiftly, one of the best strategies is to make the opponent move as fast as possible. To achieve this, the acceleration of the opponent should be maximized. Here, we consider the case in which the lighter wrestler A can produce a force of magnitude f_0 (which is supposed to be larger than f_{min}), and find the optimal force direction θ'_{opt} that generates the maximum acceleration in the heavier opponent B.

[1]Here, the reason for the use of "sufficiently" is, to be strict, in the case that Equation (11) is satisfied and the circle with radius f_0 intersects twice with the line $f_\perp = -f_\parallel/\mu_s + W$, and the range of θ is modified to:

$$arctan\, \mu_s - arccos\left(\mu_s W/\left(f_0\sqrt{1 + \mu_s^2}\right)\right) < \theta < arctan\, \mu_s + arccos\left(\mu_s W/\left(f_0\sqrt{1 + \mu_s^2}\right)\right)$$

In general, according to the Newton's second law, the acceleration of an object is determined using the equation of motion, $ma = f$, where m and f denote the mass of the object and the force acting on the object, respectively. In addition, it is known that the friction force exerted on a moving object is proportional to the normal force N, in the same way as the limiting static friction, and expressed as $\mu_{\mathrm{k}}N$, where μ_{k} is referred to as the kinetic friction coefficient [Halliday et al. (2013)].

In the situation we consider here, because the force acting horizontally on the wrestler B is $f_{\parallel} - \mu_k N_B$, the equation of motion is given by:

$$m_{\mathrm{B}} a_{\mathrm{B}} = f_{\parallel} - \mu_k N_{\mathrm{B}} \quad (25)$$

where m_{B} and a_{B} denote the mass and acceleration of B, respectively. According to Equation (2), Equation (25) is reduced to:

$$m_{\mathrm{B}} a_{\mathrm{B}} = f_{\parallel} - \mu_k (\mathrm{W} - f_{\perp}) \quad (26)$$

Assuming B is pushed by A with a force magnitude f_0 and force direction θ, then, since $f_{\perp} = f_0 \sin\theta$ and $f_{\parallel} = f_0 \cos\theta$, Equation (26) leads to:

$$m_{\mathrm{B}} a_{\mathrm{B}} = f_0 \cos\theta - \mu_k (W - f_0 \sin\theta), \quad (27)$$

which is reduced to:

$$m_{\mathrm{B}} a_{\mathrm{B}} = f_0 (\cos\theta + \mu_k \sin\theta) - \mu_k W \quad (28)$$
$$= f_0 \sqrt{1 + \mu_s^2} \cos(\theta - \phi') - \mu_k W, \quad (29)$$

where ϕ' is the angle satisfying $\tan\phi' = \mu_k$.

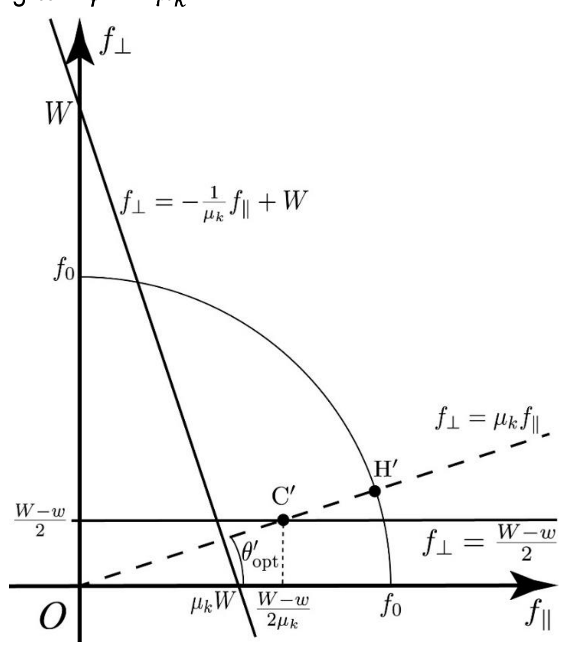

Figure 4. The direction to make the opponent move fastest θ'_{opt}.

Then, the optimal direction $\theta'_{\rm opt}$ is the direction that maximizes the right-hand side of Equation (29). Therefore, we obtain $\theta'_{\rm opt} = \phi'$, which is equivalent to the relation,

$$\tan\theta'_{\rm opt} = \mu_k \tag{30}$$

Hence, if the wrestler A pushes B with the force represented by the point H' in Figure 4, the wrestler A can make B move fastest.

However, also in this case, the vertical component of the applied force must satisfy Equation (4). In other words, the vertical component $f_\perp = f_0 \sin\theta'_{\rm opt}$ must exceed $(\mathrm{W}-\mathrm{w})/2$. Graphically, this case occurs when the force magnitude f_0 exceeds that of C' in Figure 4. In other words, when W and w satisfy the relation:

$$f_0 \geq \sqrt{\left(\frac{W-w}{2}\right)^2 + \left(\frac{W-w}{2\mu_k}\right)^2} \tag{31}$$

$$= \frac{\sqrt{1+\mu_k^2}}{2\mu_k}(W-w) \tag{32}$$

If the lighter wrestler A cannot produce a force that satisfies Equation (32), namely, if:

$$f_0 < \frac{\sqrt{1+\mu_k^2}}{2\mu_k}(W-w), \tag{32}$$

the optimal direction $\theta'_{\rm opt}$ is such that $f_\perp = (W-w)/2$ holds, which is equivalent to the relation:

$$\sin\theta'_{\rm opt} = \frac{W-w}{2f_0} \tag{32}$$

Note that this angle corresponds to the lower limit of (24).

DISCUSSION

Parameter values

Let us numerically estimate the magnitudes and directions of force obtained above by using the parameter values.

Although the static friction coefficient μ_s between clay, which forms dohyo, and the foot has never been measured to the best of the author's knowledge, we assume it at $\mu_s = 0.4$ according to a report that the static friction coefficients between the human skin and various materials mostly have a value between $0.2-0.5$ (Sivamani et al., 2003), and the fact that the value between silicon rubber and sand is less than 0.6 (Tay et al., 2015).

While the kinetic friction coefficient μ_k also seems to have never been measured, we assume it to be $\mu_k = 0.3$ because the kinetic friction coefficients are usually smaller than the static friction coefficients (Halliday et al., 2013).

In addition, when we need to give a value of the weight of the heavier wrestler in the following, we set it at $W = 150$ kgw as a typical value of sumo wrestlers.

Minimal force for sliding

The magnitude and direction of the minimal force to slide the heavier wrestler are as follows. They qualitatively depend on whether the ratio of the weights of the two wrestlers is large or small; specifically, w/W is larger or smaller than $(1-\mu_s^2)/(1+\mu_s^2)\sim 0.72$ according to the inequalities (11) and (14). For example, when the heavier wrestler's weight is $W = 150$ kgw, it depends on whether the lighter wrestler's weight is grater or smaller than $w = 108$ kgw.

When the weight of the lighter wrestler is sufficient to satisfy $w \geq 108$ kgw, the minimum force magnitude is estimated from Equation (12), which does not depend on the weight of the lighter wrester, w, and we obtain $f_{\min} = \frac{\mu_s W}{\sqrt{1+\mu_s^2}} \sim 56$ kgw. If the lighter wrestler pushes with the force stronger than this value in the direction determined from Equation (13), which is estimated as $\theta_{\text{opt}} = \arctan \mu_s = \arctan 0.4 \sim 22^{\circ}$, the wrestler can slide the heavier opponent.

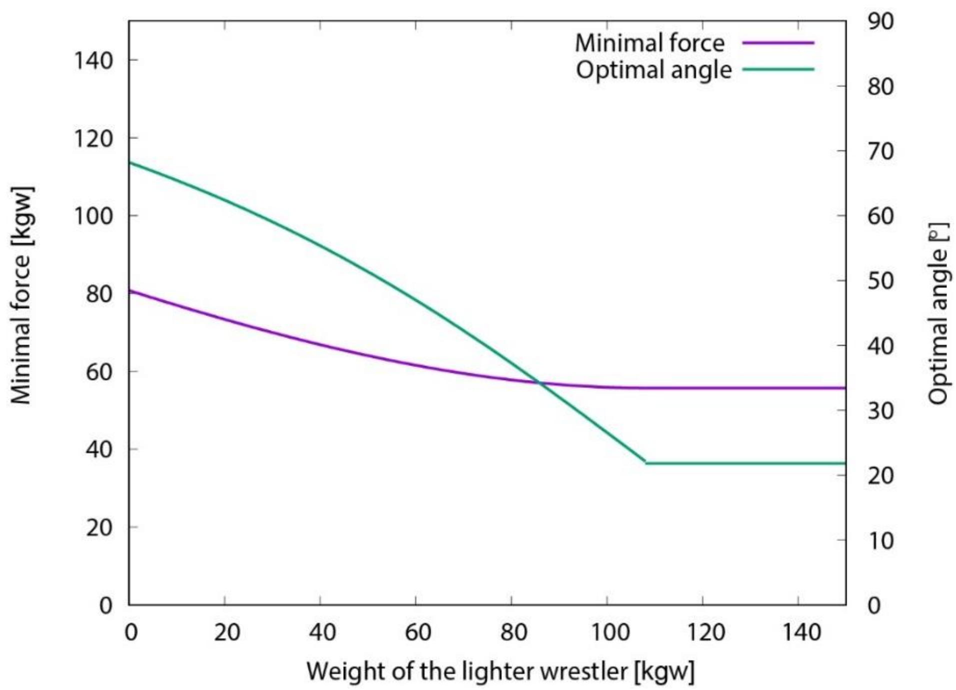

Figure 5. The magnitude and direction of the minimal force for various weights of the lighter wrestler under $\mu_s = 0.4$ and $W = 150$ kgw.

Conversely, when the lighter wrestler is so light that $w < 108$ kgw is satisfied, the minimum magnitude of force is estimated from Equation (17), which depends on the weight of the wrestler w. For example, when

$w = 90$ kgw, the heavier wrestler can slide when the lighter wrestler pushes with a force stronger than $f_{\min} = \frac{W\sqrt{\left(1-\frac{w}{W}\right)^2 + \mu_s\left(1+\frac{w}{W}\right)^2}}{2} \sim 57$ kgw in the direction determined by Equation (18), which is estimated as $\theta_{\mathrm{opt}} = \arctan((W-w)/[\mu_s(W+w)]) \sim 32^{\circ}$.

Figure 5 illustrates the $f_{\min}$ and θ_{opt} for various weights of the lighter wrestler, w.

Range of the force direction

When the lighter wrestler can exert a strong force that sufficiently exceeds $f_{\min}$, various force directions can possibly make the heavier opponent slide. The range of the force direction is given by Equation (24). For example, when the weights of the heavier and lighter wrestler are $W = 150$ kgw and $w = 90$ kgw, respectively, and if the lighter wrestler can generate a force of magnitude $f_0 = 80$ kgw, the lower limit of the angle of the direction is $\arcsin((W-w)/(2f_0)) \sim 22^{\circ}$, and the upper limit is $\arctan \mu_s + \arccos(\mu_s W/[(\sqrt{1+\mu_s^2})f_0]) \sim 68^{\circ}$.

Figure 6 presents the relation between the force magnitude and the range of the force direction in which the heavier wrestler will slide.

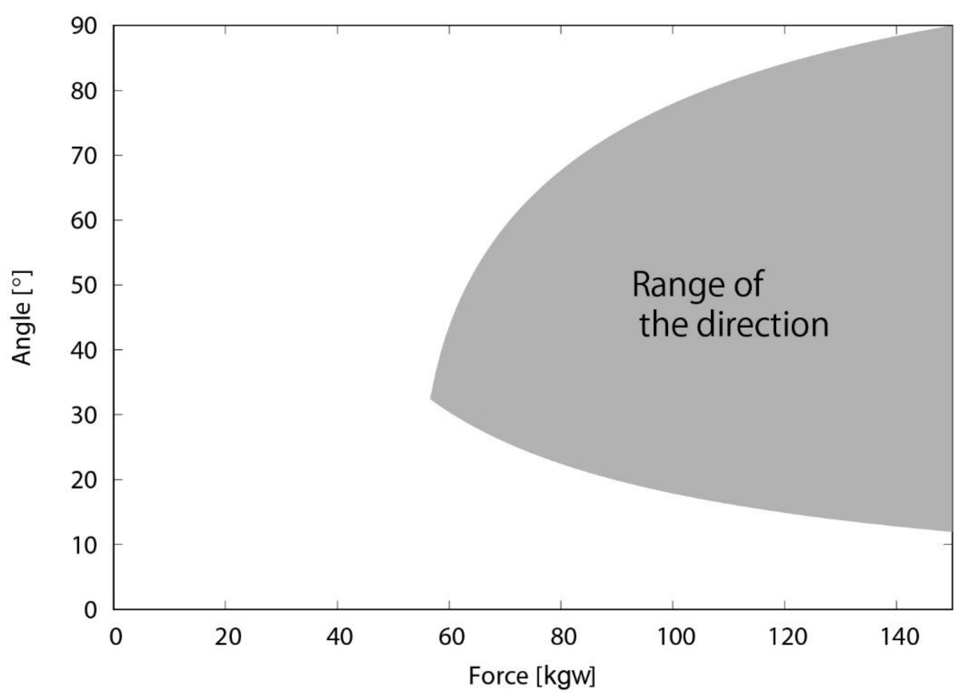

Figure 6. The force direction in which the heavier wrestler slides for various force magnitudes under $\mu_s = 0.4$, $W = 150$ kgw and $w = 90$ kgw.

Optimal force direction

Let us estimate the optimal force direction in which the lighter wrestler can make the heavier opponent move as fast as possible. The optimal force direction qualitatively depends on whether the magnitude of the force produced by the lighter wrestler exceeds $f_0 = \frac{(W-w)\sqrt{1+\mu_s^2}}{2\mu_s} \sim 52$ kgw (when $W = 150$ kgw, $w = 120$ kgw) (Equations (32) and (33)).

When the applied force magnitude f_0 is greater than 52 kgw, the optimal force direction is determined from Equation (30), that is, $\tan \theta'_{\mathrm{opt}} = \mu_k = 0.3$, which does not depend on the force magnitude f_0. Hence, the optimal way is to push in the direction of $\theta'_{\mathrm{opt}} = \arctan 0.3 \sim 17^{\circ}$.

On the other hand, when the force that can be produced is less than 52 kgw, optimal force direction is determined from (34), and depends on the force magnitude f_0. For example, when $f_0 = 40$ kgw, the optimal force direction is calculated usingsin $\theta'_{\mathrm{opt}} = (W - w)/(2f_0) \sim 0.38$. In other words, the optimal method is to push in the direction of $\theta'_{\mathrm{opt}} = \arcsin 0.38 \sim 22^{\circ}$.

Figure 7 depicts the optimal direction for various pushing forces in the case that the heavier wrestler's weight is $W = 150$ kgw and lighter's one is $w = 120$ kgw.

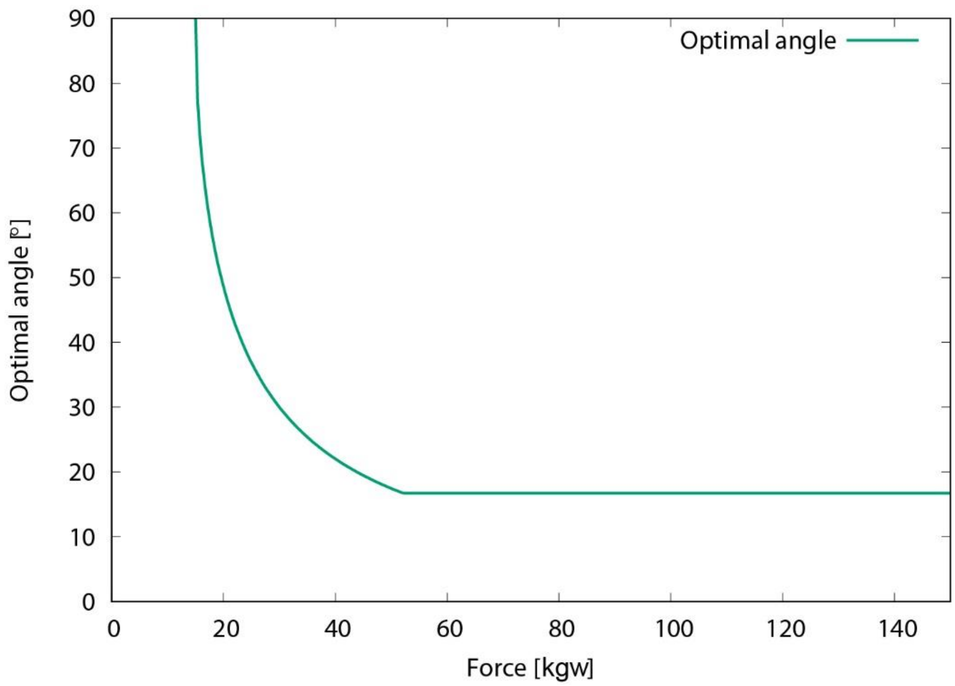

Figure 7. The optimal force direction, in which the maximum acceleration is generated in the opponent, for various force magnitudes under $\mu_{\mathrm{k}} = 0.3$, $W = 150$ kgw and $w = 120$ kgw.

CONCLUSIONS

In conclusion, mathematical formulae providing the best strategy for the lighter wrestler to win a sumo game by pushing the heavier opponent on dohyo as fast as possible is suggested as follows.

In sumo, the actual process is such that the magnitude of force increases gradually from 0 even if it occurs in a moment. Therefore, to initiate sliding the heavier opponent, the lighter wrestler should push in the direction of the minimal force. The direction of the minimal force depends on the ratio of the weights of the two wrestlers w/W. If the lighter wrestler is sufficiently heavy as $(1-\mu_s^2)/(1+\mu_s^2) < w/W$ (Equation (11)), the wrestler should push in the direction of $\theta = \arctan \mu_s$ (Equation (13)). In this case, the minimum requirement for the force magnitude is $\mu_s/\sqrt{1+\mu_s^2}$ times the heavier wrestler's weight (Equation (12)). If the lighter wrestler is so light that $w/W \leq (1-\mu_s^2)/(1+\mu_s^2)$ ((Equation (14)) is satisfied, the wrestler should push in the direction of $\theta = \arctan((W-w)/[\mu_s(W+w)])$ (Equation (18)). In this case, the minimum requirement for the force magnitude is $\sqrt{(1-w/W)^2+\mu_s(1+w/W)^2}/2$ times the heavier wrestler's weight (Equation (17)).

Once the opponent starts to slide, it is ideal for the lighter wrestler to make the opponent move as swiftly as possible. When a lighter wrester can generate a force magnitude exceeding $(W-w)\sqrt{1+\mu_s^2}/(2\mu_s)$ (Equation (32)), the wrestler should push in the direction of $\theta = \arcsin((W-w)/(2f_0))$ (Equation (33)).

In a real game, the heavier opponent will of course not be static but push the lighter wrestler. Nevertheless, we should note that the above analysis is still effective; all the above results can be derived similarly if we replace the force generated by the lighter wrestler to the sum of the force generated by both the lighter and heavier wrestler in the equations above. Some future studies can be carried out to obtain more realistic predictions. Since the friction coefficient is the key to determine the forces calculated above, measurement of the static and kinetic friction coefficients would be important to find the best strategy for sumo wrestlers. In addition, although it is assumed in this study for simplification that the force magnitude generated by the wrestlers does not depend on the direction, in reality, the available force magnitude would depend on the direction θ, and be a function of the direction, $f(\theta)$. Nevertheless, the logic of the analysis would not be modified; instead of drawing a circle of the radius of f_0 in Figure 3 and Figure 4, we only have to draw the graph of $f(\theta)$, and carry out the analysis in the same manner. To obtain predictions that is more applicable to the real game, measurement of $f(\theta)$ would be meaningful.

Finally we should note that the importance of this study is not limited to sumo; the result can be applied to all situations where we carry an object by sliding on the floor. We can do it most effectively if we push the object to the direction given by Equation (13) or (18) to initiate the sliding, and to the direction given by Equation (30) or (34) after the initiation of the sliding.

SUPPORTING AGENCIES

This work is supported by the Grants-in-Aid for Scientific Research (KAKENHI) program of the Japan Society for the Promotion of Science (Grant Number 20K03775).

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ACKNOWLEDGEMENTS

The author is grateful to Yukio Abe, Yoshiyuki Enomoto and Ryosuke Ishiwata for critical reading of the manuscript.

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