Considerations on the Kinetics of the Sine Wave through the Example of gunnun so ap joomuk kaunde baro ap jirugi

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The more I know, the more I realize I know nothing.

Albert Einstein
(translated from German)

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1 Introduction

1.1 Problem Statement

> To create a sine wave during the movement by utilizing the knee spring properly. [sic!] (Choi, 1999, p. 42)

The 8th training secret in Taekwon-Do demands the execution of a wave in movements. Consequently, the wave can be regarded as one of the central principles in patterns (Tul) and fundamental techniques.

According to the theory of power (Him Ui Wolli), the wave is meant to integrate body weight into a technique, allowing the body to fall into the technique. This, in turn, is supposed to increase the force of a technique. (Choi, 2003, p. 58)

Taekwon-Do, according to its founder, is a martial art of self-defence that is superior to all others in terms of strength and technique. It also aims to enhance intellectual capabilities through the scientific application of Taekwon-Do. (Choi, 2003, pp. 9, 15)

However, within both the martial arts and combat sports communities, there is considerable debate between supporters and opponents of the sine wave regarding its necessity and effectiveness. Proponents argue that allowing the body to fall into a technique efficiently generates force (Nardizzi, 2017), whereas critics view the wave as an abstract theory that contradicts the physics of real combat situations (Djurdjevic, 2009).
Observing fights in K1 or MMA, which accommodate all martial arts and combat sports styles, one finds that a concept based on the sine wave is rarely, if ever, applied.

Starting from Choi Hong Hi's assertion that Taekwon-Do surpasses other martial arts in power and technique, this thesis seeks to determine whether the wave contributes to an increase in physical force and, if so, to quantify this additional force.

1.2 Objective and Scope

The objective of this thesis is to develop a simple mathematical model based on fundamental physical principles. The model will be implemented through software to analyse the force generation facilitated by the sine wave.

The movements of the human body are composed, among other things, of the interaction of many muscles and joints. As a result, a human movement exhibits a high level of complexity due to the numerous components involved. In the context of this thesis, it therefore does not seem practical to consider the wave in its entirety for the large number of movements in Taekwon-Do. For this reason, the model to be developed in this thesis is limited to a single step of *gunnun so ap jumok kaunde baro ap jirugi* into *gunnun so ap jumok kaunde baro ap jirugi*. This movement and technique is fundamental and practiced by both beginners and advanced students. Furthermore, in these two techniques, a complete wave motion is performed along with a forward step, allowing the wave to fully unfold its potential.

1.3 Structure

Chapter 2, starting on page 3, briefly outlines the mechanical principles of potential and kinetic energy, momentum, force, as well as the movement in *gunnun so ap joomuk kaunde baro ap jirugi*, with and without wave motion.

Chapter 3, beginning on page 9, introduces the methodology and software employed in this thesis.

The design and implementation of the model, along with the theoretical considerations that guided it, are presented in Chapter 4, starting on page 10.

Chapter 5, from page 16 onward, discusses and analyses the results obtained from the model.

Finally, Chapter 6, beginning on page 22, summarises the key findings and provides suggestions for further refinement and extension of the model.

2 Fundamentals

2.1 Mechanics

2.1.1 General Quantities

When analysing the human body concerning vectorial quantities such as momentum and force, mass and velocity are crucial factors.

Mass represents body mass, measured in kilograms (kg). During a punch, only part of the body's mass is involved in generating force. This is referred to as the effective mass in this thesis.

The mean velocity $\vec{v}$ of an object moving along a distance d over time t is given by formula 1. $\vec{v}$ is a vectorial quantity and is specified in metre per second ($\frac{\mathrm{m}}{\mathrm{s}}$).

$$\vec{v} = \frac{d}{t} \tag{1}$$

2.1.2 Resultant

Figure 1 shows a right-angled triangle. The straight lines are the catheti, a and b, that are perpendicular to each other and the straight line c is the hypotenuse. The triangle is the foundation for undertanding the Pythagoras

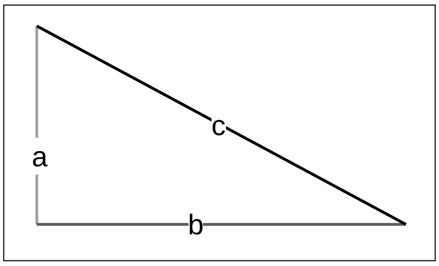

Figure 1: Right-angled triangle

theorem in formula 2.

$$c^2 = a^2 + b^2 \tag{2}$$

The theorem enables the determination of the resultant vector from figure 2. In this context, the hypotenuse corresponds to the resultant vector, while the adjacent and opposite catheti correspond to the horizontal and vertical vectors, respectively.

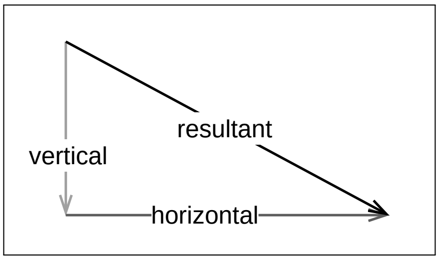

Figure 2: Resultant vector

2.1.3 Energy

Regarding an object – such as the human body – energy can be physically distinguished into potential energy (E_{pot}), also called elevational energy, and kinetic energy (E_{kin}), also known as motion energy. Both forms of energy are measured in joules (J).

The potential energy of an object with mass m and height h in meters (m) is calculated according to formula 3, taking into account the acceleration due to gravity g. g is $9,81\text{m/s}^2$.

$$E_{pot} = mgh \tag{3}$$

The kinetic energy of an object with mass m and velocity $\vec{v}$ is given by formula 4.

$$E_{kin} = \frac{1}{2}m\vec{v}^2 \tag{4}$$

2.1.4 Momentum and Force

Newton's second law describes the force $\vec{F}$ using the mass m and the acceleration $\vec{a}$ according to formula 5.

$$\vec{F} = m\vec{a} \tag{5}$$

The law can also be described as momentum in classical mechanics according to formula 6, as only the velocity $\vec{v}$ changes, but not the mass m (Taylor, 2014, p. 36).

$$\vec{p} = m\vec{v} \tag{6}$$

Force can be defined as the change in momentum Δp over the change in time Δt according to formula 7.

$$\vec{F} = \frac{\Delta p}{\Delta t} \tag{7}$$

2.1.5 Relationship between the Quantities

From Figure 3, the relationships between the individual mechanical quantities – kinetic energy E_{kin}, momentum $\vec{p}$, and force $\vec{F}$ can be derived.
In the top left, the kinetic energy is shown, which is a scalar quantity and practically forms the foundation for momentum. Momentum, in turn, is a vector quantity that generates a force upon impact with an object, which

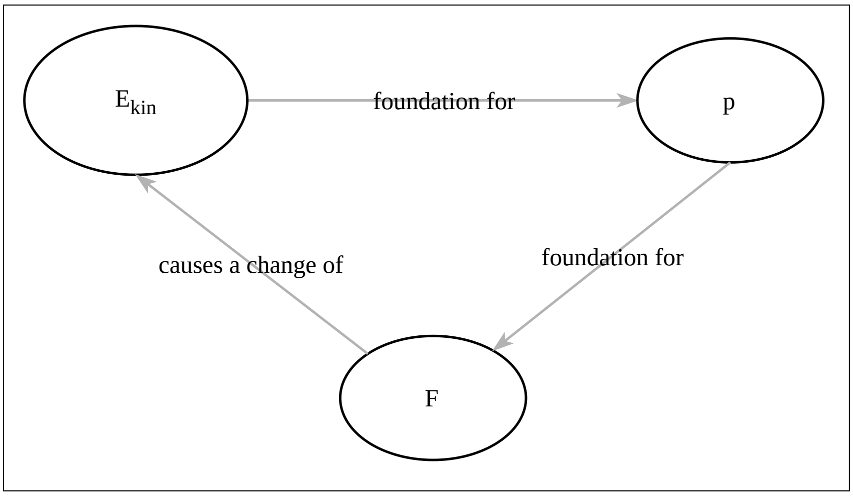

Figure 3: Relationship of the physical quantities to each other

is also directed. When this force acts on an object, it changes its kinetic energy.

2.2 Movement with Wave

In Figure 4, the wave during a forward movement in *gunnun so ap joomuk kaunde baro ap jirugi* is schematically depicted. The starting point of the forward movement is also the technique *gunnun so ap joomuk kaunde baro ap jirugi*, which is shown on the far left in black. Both techniques can also be found in Choi, 2003, p. 58.
The new movement begins with a relaxation (light gray) and leads into an upward (gray) and then a downward movement (black). Therefore, a wave can be divided into three phases: the relaxation, upward, and downward phases.[1] These phases can be mapped to the amplitudes and the zero point on the y-axis of an idealized sine wave, which is phase-shifted by $-\pi$ on the

[1]A wave can also have fewer phases. However, since this does not have direct relevance in the further course of this thesis, it will not be discussed further here.

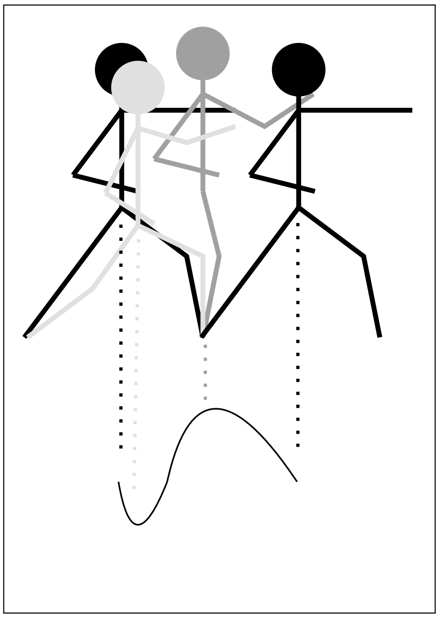

Figure 4: Movement with wave

x-axis.

In Figure 5, the three phases of a wave are shown separately. At the

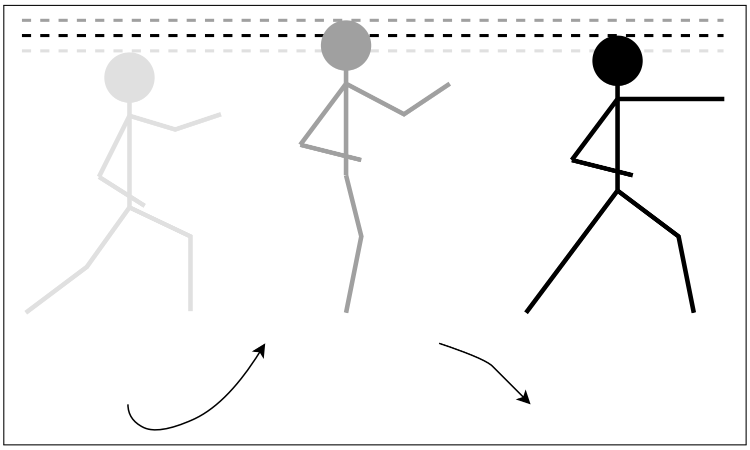

Figure 5: Relaxation, upward, and downward phases of a wave

end of the various phases, the body is at different heights, indicated by the dashed lines.
At the beginning of the relaxation phase, drawn in light gray on the far left, both knees bend due to the relaxation, causing the body to slightly sink

downward and forward. As the body sinks, it reaches the lowest point of the wave, which is indicated by the light gray dashed line.
In the subsequent upward phase, the counter-movement of the arms is executed, and both legs are stretched, with the rear leg moving the body forward and the front leg moving the body upward. At the highest point during the wave – represented by the gray dashed line – both legs are stretched to a slight bend, and the center of mass of the body is over or just behind the supporting foot, in the direction of the technique being executed.
After the highest point is reached, the downward phase (represented in black) begins. During this phase, both arms are accelerated so that the technique hits the target with maximum speed. The body falls downward into the technique during the forward movement due to the vertical velocity (Choi, 2003, p. 58). Since both legs are almost fully extended after the upward phase, the body can only be accelerated slightly in the horizontal direction during the downward phase by extending the supporting knee. Once the downward phase is completed, the entire movement concludes. The body is now at a middle height, as indicated by the black dashed line. Throughout the entire movement, the arms and legs should remain slightly bent, and the eyes, hands, feet, and breathing should be coordinated as described in the 6th and 3rd training secrets (Choi, 2003, p. 42).

Figure 6 shows the ends of the upward (gray) and downward (black) phases, as well as the height the body reaches, represented by the gray and black dashed lines. The difference between the two lines can be interpreted as

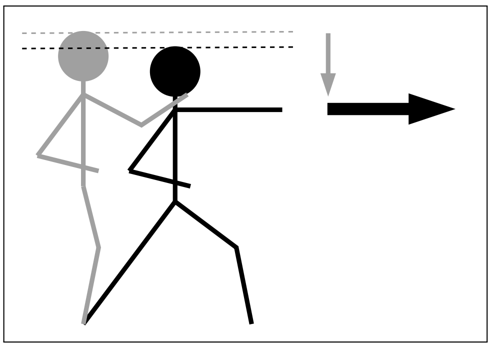

Figure 6: Vertical and horizontal movement of the body

the distance the body lowers, meaning the vertical movement. The vertical distance is schematically represented by the gray arrow, while the horizontal distance during the forward movement of the body is represented by the black one. Thus, two movements of the body or distances can be identified during the downward phase: a vertical and a horizontal movement or rather distance.

2.3 Movement without Wave

A movement as it could be executed without a wave is shown in Figure 7. This type of movement would begin with a starting phase (left), transition

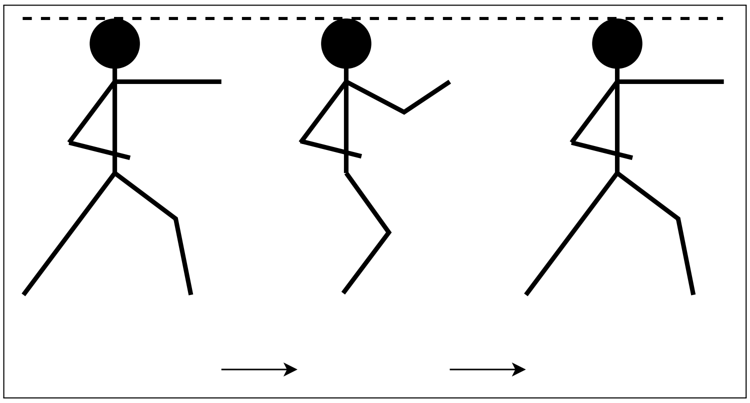

Figure 7: Movement without wave

through a middle phase (center), and conclude with an ending phase (right). The body remains at the same height throughout all phases, so there is only horizontal movement. In contrast to the movement with a wave, the body could not be involved in the technique through a lowering action. However, because the supporting leg would be more deeply bent during the middle phase, the extension of the supporting leg could be used to generate a possibly higher horizontal velocity of the body into the technique.
Furthermore, a lower stance allows for greater acceleration of the body in the direction of movement than a higher stance (Pfeifer, 2006, p. 103). This corresponds to the lower position of the body in the middle and ending phases, achieved by the more deeply bent supporting leg.

Such a movement is considered incorrect in Taekwon-Do (Choi, 2003, p. 58).

3 Methodology

Based on theoretical considerations and reflections, a simple mathematical model is created, which helps trace and analyze the influence of the wave on potential force development.
First, the kinetics with and without the wave are calculated, followed by the force resulting from the momentum. The conclusion of the model development involves a semantic partial validation of the model using published values, which are used as input parameters.
Subsequently, the model is used to specifically examine the influence of the wave on various physical components and quantities. No measured real data is used to avoid the effort involved in data privacy concerns.

The model is implemented in Python version 3.1 (Python Software Foundation, n.d.).
The text is written in LaTeX 3 (The Latex Project, n.d.) with the help of TexStudio 4.2.1 (van der Zander et al., n.d.). The graphics are from drawio 26.0.9 ("draw.io", n.d.). The reference management tool used is JabRef 3.8.2 (Chen et al., n.d.).
ChatGPT ("ChatGPT", n.d.) was used as a sparring partner for developing the physical fundamentals and their relation to martial arts, as well as for translating from German to English.

4 Model

4.1 Kinetics with Wave

4.1.1 Body

The vertical and horizontal motion components from the downward phase of the wave are considered as the momentum $\vec{p}_{vertical}$ and $\vec{p}_{horizontal}$. To determine the resulting momentum $\vec{p}_{body\_wave}$, the Pythagorean theorem can be applied according to equation 8:

$$\vec{p}_{body\_wave} = \sqrt{(\vec{p}_{vertical})^2 + (\vec{p}_{horizontal})^2} \tag{8}$$

The velocity $\vec{v}$ for $\vec{p}_{vertical}$ can be derived using the equations for potential energy (E_{pot}) and kinetic energy (E_{kin}). The key assumption is that the potential energy of the body at the end of the upward phase is fully converted into kinetic energy by the end of the downward phase, so that $E_{pot} = E_{kin}$ holds. Equation 9 shows the derivation of the velocity for $\vec{p}_{vertical}$, leading to $\sqrt{2gh}$ as an expression for $\vec{v}$:

$$E_{pot} = E_{kin} \Rightarrow mgh = 1/2m\vec{v}^2 \Rightarrow gh = 1/2\vec{v}^2 \Rightarrow \vec{v} = \sqrt{2gh} \tag{9}$$

Thus, the vertical momentum $\vec{p}_{vertical}$ follows equation 10:

$$\vec{p}_{vertical} = m_{effective} * \sqrt{2gh} \tag{10}$$

The horizontal momentum $\vec{p}_{horizontal}$, considering the effective mass $m_{effective}$ and the horizontal velocity $\vec{v}_{horizontal}$, is given by equation 11:

$$\vec{p}_{horizontal} = m_{effective} * \vec{v}_{horizontal} \tag{11}$$

4.1.2 Body and Fist

For the calculation of the momentum of body and fist movement, the different velocity vectors are first considered, as the resulting vector can be used to determine the momentum.

There are three velocity vectors: the vertical and horizontal body movements $\vec{v}_{body\_vertical}$, $\vec{v}_{body\_horizontal}$, as well as the fist movement $\vec{v}_{fist}$. Since $\vec{v}_{horizontal\_total}$ and $\vec{v}_{fist}$ are parallel, they can be directly summed to form the total horizontal velocity $\vec{v}_{horizontal\_total}$.

$$\vec{v}_{total} = \sqrt{(\vec{v}_{horizontal\_total})^2 + (\vec{v}_{body\_vertical})^2} \tag{12}$$

Using $\vec{v}_{horizontal\_total}$ and $\vec{v}_{body\_vertical}$, the resulting velocity $\vec{v}_{fist}$ can now be determined according to equation 12.

Based on the total velocity, the total momentum can then be calculated using equation 13:

$$\vec{p}_{total} = m_{effective} * \vec{v}_{total} \tag{13}$$

4.2 Kinetic without Wave

4.2.1 Body

Without a wave, the momentum of the body $\vec{p}_{body\_no\_wave}$ can be directly calculated using equation 14, based on the effective mass $m_{effective}$ and the horizontal velocity $\vec{v}_{horizontal}$.

$$\vec{p}_{body\_no\_wave} = m_{effective} * \vec{v}_{horizontal} \tag{14}$$

4.2.2 Body and Fist

The horizontal body movement and the movement of the fist occur parallel at the end of the total movement. As a result, the total velocity $\vec{v}_{total}$ can be directly determined from the velocity of the body $\vec{v}_{body}$ and the velocity of the fist $\vec{v}_{fist}$ using equation 15.

$$\vec{v}_{total} = \vec{v}_{body} + \vec{v}_{fist} \tag{15}$$

4.3 From Momentum to Force

Depending on the duration of the impulse, force is generated in its direction. This happens, for example, when the fist – using the knuckles of the middle fingers as the contact surface – strikes a target.

4.4 Velocities

In this subsection, the horizontal velocity of the body as well as the fist strike is discussed.

Many everyday velocities are given in $\frac{\mathrm{km}}{\mathrm{h}}$. For the calculation of momentum, these must be converted to $\frac{\mathrm{m}}{\mathrm{s}}$. $1\frac{\mathrm{m}}{\mathrm{s}}$ corresponds to $3.6\frac{\mathrm{km}}{\mathrm{h}}$.[2]

[2] The corresponding conversion is listed in Chapter A.1 on page 26.

Table 1 shows estimated horizontal velocities of a walker and a long-distance runner. The velocities are provided in both $\frac{km}{h}$ and $\frac{m}{s}$. The latter were calculated based on the consideration outlined above and rounded to the first decimal place. The velocities of a walker range from 3 to 5 $\frac{km}{h}$, which

	Minimum $\frac{km}{h}$	Maximum $\frac{km}{h}$	Minimum $\frac{m}{s}$	Maximum $\frac{m}{s}$
Walker	3	5	0.8	1.4
Long-distance runner	8	12	2.2	3.3

Table 1: Estimated velocities

corresponds to 0.8 to 1.4 $\frac{m}{s}$. A long-distance runner, according to estimates, can reach velocities between 8 and 12 $\frac{km}{h}$, which translates to 2.2 to 3.3 $\frac{m}{s}$.

To estimate the velocity of a punch, Choi, 2003, p. 63 is referenced. There, an image of a punch experiment is shown. At 30 flashes per second, the fist is seen in both an intermediate and final position. From this, it can be deduced that the punch corresponds to 2 flashes, or 1/15 seconds, thus taking approximately 0.07 seconds. At this point, it is assumed that the length of the arm, and therefore the distance traveled by the fist, is 80 cm. This corresponds to a velocity of 13.3 $\frac{m}{s}$.[3] Other measured values average around 9.2 $\frac{m}{s}$ (Ishac & Eager, 2021).
In this examination, it is assumed that a punch can be executed with a velocity of 10 $\frac{m}{s}$.

4.5 Effective Mass

The distribution of body mass across the torso, limbs, and head is not consistently described in the literature (Pfeifer, 2010). In this thesis, it is assumed that approximately only half of the body mass can be effectively used in both vertical and horizontal movement.

4.6 Structure

The implemented model consists of five sections: input (listing 1), anthropometric data (Anthropometry, listing 2), data for movement execution with a wave (Wave, listing 3) and without a wave (No Wave, listing 4), as well as a comparison between the movement execution with and without a wave

[3] The corresponding calculation is listed in Chapter A.1 starting on p. 26.

(Comparison, listing 5). The inputs are marked with the symbol $> -$, and the outputs with $- >$.

Listing 1: Inputs for the calculation

```
Input
>- vertical distance (m):
>- mass (kg):
>- velocity body wave (m/s):
>- velocity body no wave (m/s):
>- velocity fist (m/s):
>- pulse duration (sec):
```

When executing the model, the inputs for the vertical distance during the wave (vertical distance), body mass (mass), horizontal velocity of the body during the wave (velocity body wave) and without the wave (velocity body no wave), as well as the impulse duration (pulse duration), must be provided.

Listing 2: Output of the anthropometric data

```
Anthropometry
-> effective mass factor: 0.50
-> effective mass:
```

The calculation for the effective mass[4] within the anthropometric data is based on the factor for the effective mass (effective mass factor). This is assumed to be 0.5 in the model and is defined as a constant.

Listing 3: Output of the movement data with wave

```
Wave
-> velocity body vertical:
-> momentum body vertical:
-> momentum body horizontal:
-> momentum body:
-> force body:
-> velocity total:
-> momentum total:
-> force total:
```

The calculations for the movement with wave include the vertical velocity of the body (velocity body vertical), the vertical (momentum body vertical) and horizontal momentum of the body (momentum body horizontal), the resultant momentum of the body and thus the wave's momentum (momentum body), the force generated by the body (force body), the resultant velocity for the vertical and all horizontal velocities (velocity total), the resultant of all momenta (momentum total), as well as the resultant of all forces (force total).

[4]See also Chapter 2.1.1 starting from p. 3.

Listing 4: Output of movement data without wave

```
No Wave
-> momentum body:
-> force body:
-> velocity total:
-> momentum total:
-> force total:
```

The calculations for the movement without the wave include the momentum for the body (momentum body), the force that can be applied by the body (force body), the velocity resulting from both the body and fist movement (velocity total), the total momentum (momentum total), and the total force (force total).

Listing 5: Output of the comparison data

```
Comparision
-> wave more force:
```

The last section contains the percentage indicating whether the movement with the wave generates more or less force than the movement without the wave (wave more force/wave less force).

4.7 Semantic Validation

The model developed in this thesis is semantically validated using data from Ishac and Eager, 2021.[5] The data includes measurements of a punch executed with a wave movement. At this point, only the calculated force values are checked for plausibility by comparing them with those from the publication. Excerpts of the model's inputs and outputs can be seen in listing 6.

Listing 6: Inputs and outputs of the model

```
########################################
Input
>- vertical distance (m): 0.15
>- mass (kg): 125
>- velocity body wave (m/s): 1.4
>- velocity body no wave (m/s): 1.4
>- velocity fist (m/s): 9.2
>- pulse duration (sec): 0.1

----------------------------------------

Anthropometry
```

[5]The model can be executed online ("Python Online Compiler", n.d.) using the source code from Chapter A.2 starting from p. 26.

```
...

----------------------------------------

Wave
...
-> force total: 6711.20 N

----------------------------------------

No Wave
...
-> force total: 6625.00 N

----------------------------------------

Comparison
-> wave more force: 1.28 %

########################################
```

In one of the experiments by Ishac and Eager, 2021, a 125 kg Taekwon-Doin executes a punch with an average speed of 9.2 $\frac{m}{s}$. Three measured force values fall within the interval [5342N, 8834N], with an average of 6884 N. The vertical distance is estimated at 0.15 m due to the practitioner's body weight. It is also assumed that the horizontal velocity of the body, both with and without a wave, is 1.4 $\frac{m}{s}$. Additionally, an impulse duration of 0.1 seconds is considered.
The force calculated by the model for movement with a wave is 6711.2 N, which is less than 200 N below the average value and falls within the published range for fist strikes with a wave from Ishac and Eager, 2021.
Thus, it is assumed that the developed model correctly calculates the force generated by a movement with a wave. The percentage calculation is also validated, as demonstrated in equation 16.

$$100 - \frac{100 * 6625}{6711.2} = 1.28 \tag{16}$$

5 Results and Discussion

5.1 Greater Force Application

To gain an impression of potential force values in overall movement when using a wave, this section examines the three theoretical profiles – large, medium, and small – along with their respective values calculated by the model.
The large profile represents a 110 kg Taekwon-Doin who moves 0.15 m downward during the wave's downward phase. The medium profile corresponds to an 80 kg Taekwon-Doin with a downward movement of 0.1 m during the wave. The small profile represents a 50 kg Taekwon-Doin executing a 0.05 m vertical movement during the wave.
The horizontal velocities for movement with and without the wave are 1.4 $\frac{\mathrm{m}}{\mathrm{s}}$ across all profiles. Similarly, the punch velocity is assumed to be 10 $\frac{\mathrm{m}}{\mathrm{s}}$, and the impulse duration is consistently set to 0.1 seconds for all cases.[6]

Table 2 displays, in addition to the vertical distance and body weight, the calculated values for the three profiles. It is noticeable that the values

profile	height [m]	mass [kg]	$\vec{v}_{total}[\frac{m}{s}]$	$\vec{f}_{total}[N]$	$\vec{f}$ [%]
large	0.15	110	11.53	6341	1.11
medium	0.1	80	11.49	4594	0.75
small	0.05	50	11.44	2861	0.38

Table 2: Result values of higher force conversion

for the large profile show the highest figures, with a total velocity ($\vec{v}_{total}$) of 11.53 $\frac{\mathrm{m}}{\mathrm{s}}$ and a total force ($\vec{f}_{total}$) of 6341 N. Moreover, the large profile can best utilize the wave for force conversion, achieving an increase of 1.11%. The values for the medium profile are in the middle, with $\vec{f}_{total}$ of 11.49 $\frac{\mathrm{m}}{\mathrm{s}}$ and $\vec{f}_{total}$ of 4594 N. The wave utilization for force conversion in this profile stands at 0.75%, placing it between the other two profiles. The small profile exhibits the lowest values, with $\vec{v}_{total}$ of 11.44 $\frac{\mathrm{m}}{\mathrm{s}}$ and $\vec{f}_{total}$ of 2861 N. Additionally, this profile can utilize the wave the least effectively, leading to only a 0.38% increase in force compared to movement without the wave.

Overall, the results indicate that movement with wave enables higher force conversion than movement without wave across the given parameters.

[6] The model input and output data can be found in chaper B.1 in listing 8, 9 and 10 starting on p. 30.

It is also not surprising that a larger and heavier Taekwondo practitioner exhibits higher total force values compared to lighter and smaller practitioners. However, it is noteworthy that, based on the calculated values, the larger practitioner can more effectively utilize the wave for force conversion in relation to their weight compared to smaller individuals. This can be explained by the fact that the additional force generated by the wave depends on the potential energy from the downward movement, which is linked to the vertical velocity. The vertical velocity, in turn, depends on the length of the vertical distance covered.

5.2 Body Momentum and Transferred Force

The given subchapter examines the body's movement component during the downward phase of the wave in relation to the momentum and the force that can be applied through the momentum.

Table 3 shows the momenta and forces that occur at the estimated minimum and maximum speed of a pedestrian[7] both with and without the wave, with the entries sorted in ascending order based on the magnitude of the momentum and force values. The vertical distance is 0.1 m, the speed of the fist is 10 $\frac{\mathrm{m}}{\mathrm{s}}$, and the pulse duration is 0.1 seconds.[8]

movement	velocity $[\frac{\mathrm{m}}{\mathrm{s}}]$	momentum $[\mathrm{kg} * \frac{\mathrm{m}}{\mathrm{s}}]$	force [N]
no wave	0.8	32	320
no wave	1.4	56	560
wave	0.8	65	645
wave	1.4	79	792

Table 3: Resulting values for body momenta and forces

First of all, it is noticeable that for both horizontal velocities, the movements with wave exhibit a higher momentum than the movements without wave. Thus, for a movement without a wave, the momentum is 32 and 56 $\mathrm{kg} * \frac{\mathrm{m}}{\mathrm{s}}$ at horizontal speeds of 0.8 and 1.4 $\frac{\mathrm{m}}{\mathrm{s}}$, respectively, with the force being 320 and 560 N. For the movements with wave at 0.8 and 1.4 $\frac{\mathrm{m}}{\mathrm{s}}$, the momentum is 65 and 79 $\mathrm{kg} * \frac{\mathrm{m}}{\mathrm{s}}$, and the force is 645 and 792 N, respectively.

[7]See Chapter 4.4 starting from p. 11.

[8]The model input and output can be found in chaper B.2 in listing 11 and 12 starting on p. 32.

At lower horizontal speeds, it can be assumed that the wave leads to higher force development. Even a movement with a wave and a lower horizontal speed of 0.8 $\frac{m}{s}$ results in higher force development than a movement without a wave but with a higher horizontal speed of 1.4 $\frac{m}{s}$.

It should be noted, however, that the horizontal speed cannot be arbitrarily fast or slow, as according to the third training secret, the eyes, hands, feet, and breathing must be coordinated. This means that the technique must be completed with the stance being taken. Therefore, the vertical movement of the body must also be completed in conjunction with the horizontal movement.

At this point, the following should be noted. The practice of Taekwon-Do serves, among other things, health purposes (Choi, 2003, p. 15). Due to the third training secret in conjunction with the wave, the situation depicted in Figure 8 arises. The wave strengthens the body's momentum in a downward

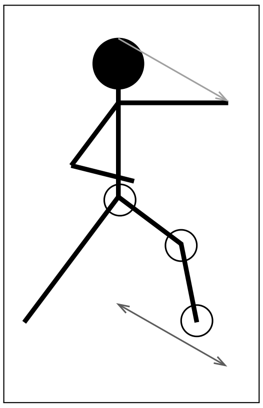

Figure 8: Reactive forces on the hip joint

direction. At the same time, however, the jump, knee, and hip joints must not convert the momentum into kinetic energy through their natural function by absorbing the momentum through the muscles.
As a result, the forces generated at the end of the movement are transmitted from the ground through the front foot, the front knee, and into the hip joint. Thus, the forces of the movement ultimately act largely on the hip joint. As the numbers above show, these forces can reach up to 792 N, and even more for heavier and larger Taekwon-Doin.
Such a movement could have negative consequences for the hip joint in the long term due to excessive strain.

5.3 Vertikal Distance

In this subsection, the significance of the vertical distance during the downward phase of the body and the associated force exerted by the complete movement of the body and fist is highlighted. The input parameters for the calculations are as follows. It is assumed that the Taekwon-Doin weighs 80 kg. This practitioner moves their body with a horizontal velocity of 1.4 $\frac{\text{m}}{\text{s}}$, while the relative velocity of the fist is 10 $\frac{\text{m}}{\text{s}}$. Furthermore, a pulse duration of 0.1 seconds is assumed. To understand the influence of the vertical distance, values of 0.15 m, 0.1 m, and 0.05 m are considered for this parameter.[9]

The calculated values for the vertical velocity ($\vec{v}_{vertical}$), the total velocity ($\vec{v}_{total\_wave}$), and the applied force (f_{total_wave}) can be found in Table 4. The table is sorted in descending order according to the values. For a vertical

$\vec{d}_{vertical}[m]$	$\vec{v}_{vertical}[\frac{m}{s}]$	$\vec{v}_{total\_wave}[\frac{m}{s}]$	f_{total_wave}
0.15	1.72	11.53	4611
0.1	1.4	11.49	4594
0.05	0.99	11.44	4577

Table 4: Results of the vertical distances

distance of 0.15 m, the values are the highest, with a vertical velocity of 1.72 $\frac{\text{m}}{\text{s}}$, a total velocity of 11.53 $\frac{\text{m}}{\text{s}}$, and a total force of 4611 N. The values for a vertical distance of 0.1 m are in the middle, with a vertical velocity of 1.4 $\frac{\text{m}}{\text{s}}$, a total velocity of 11.49 $\frac{\text{m}}{\text{s}}$, and a total force of 4594 N. The lowest values are recorded for a distance of 0.05 m, amounting to 0.99 $\frac{\text{m}}{\text{s}}$ for vertical velocity, 11.49 $\frac{\text{m}}{\text{s}}$ for total velocity, and 4577 N for total force.

First, it is noted that body mass has no influence on vertical velocity and, consequently, on total velocity. This can be mathematically observed in the calculation of vertical velocity, where mass does not appear.
Thus, it can be concluded that the vertical distance is a crucial factor in force generation through the wave motion.

5.4 Maximum Force Application

The previous results suggest, and the formulas for kinetic energy and momentum show, that velocity is an important factor in force conversion. With

[9]The corresponding model inputs and outputs can be found in chaper B.2, listing 13, 14 und 15 starting from p. 34.

a maximum relative speed of the fist, additional force can only be converted through the body movement, such as through the wave. However, beyond a certain horizontal velocity of the body, a movement with a wave seems no longer feasible. One can think of a sprinter, who pushes off from a standstill and rockets forward. In such a movement with maximum acceleration through the leg extension, only the most direct path can be taken. This aspect is taken into account here by examining the influence of horizontal speeds ($\vec{v}_{horizontal}$) of 2.2 and 3.3 $\frac{\text{m}}{\text{s}}$ on the total speed $\vec{v}_{total}$ and total force $\vec{f}_{total}$. For comparison, a movement with a wave and a horizontal body movement of 1.4 $\frac{\text{m}}{\text{s}}$ is presented. The comparison is shown via the percentage (more $\vec{f}$).
To establish a uniform starting basis, an 80 kg Taekwon-Do practitioner is assumed, who covers a vertical distance of 0.1 m during the wave. The relative speed of the punch is $\frac{\text{m}}{\text{s}}$, and the impulse duration is 0.1 seconds.[10]

movement	$\vec{v}_{horizontal}[\frac{m}{s}]$	$\vec{v}_{total}[\frac{m}{s}]$	$\vec{f}_{total}[N]$	more $\vec{f}$ [%]
wave	1.4	11.5	4594	-
no wave	2.2	12.2	4880	6
no wave	3.3	13.3	5320	14

Table 5: Result values of the maximum forces

The calculated and rounded values, along with horizontal speed, are shown in Table 5, sorted in ascending order. A movement with a wave, starting from a horizontal speed of 1.4 $\frac{\text{m}}{\text{s}}$ achieves a total speed of 11.5 $\frac{\text{m}}{\text{s}}$ and exerts a force of 4594 N. Without the wave, a horizontal body speed of 2.2 $\frac{\text{m}}{\text{s}}$ results in a total speed of 12.2 $\frac{\text{m}}{\text{s}}$ and a total force of 4880 N. The highest values, 13.3 $\frac{\text{m}}{\text{s}}$for total speed and 5320 N for total force, occur with a horizontal body speed of 3.3 $\frac{\text{m}}{\text{s}}$.

Compared to the wave movement, movements without the wave can theoretically achieve 6 to 14 % higher force values due to the higher total speed. However, since the horizontal speeds for the movements without the wave are estimated values, these higher force values should not be considered as facts at this point.

Furthermore, measurements by Ishac and Eager, 2021 indicate that a

[10]The corresponding model input and output data can be found in chaper B.4, listing 16 and 17 starting from p. 36.

Taekwon-Do fist strike with a wave, in terms of the force-to-body weight ratio, has a lower ratio compared to punches from other martial arts. The Taekwon-Do technique with a wave has a ratio of 55:1, while punches from other martial arts have ratios of 70:1 or even 82:1 (Ishac & Eager, 2021).

Additional evidence that movements without a wave may generate higher forces comes from the competition discipline of the power breaking test. This discipline focuses on applying maximum force. Many successful competitors do not use a wave when executing the punch. This has been observed in Demarchi, 2022; International Taekwon-Do Federation, 2016, 2019.
It should be noted here that the force in a wave is ideally aligned with the resultant of the vertical and horizontal momentum of the body. In the case of the power breaking test, the boards to be broken with the fist should be aligned along the impulse or force resultant. For the punch, this would be slightly downward.

6 Conclusion and Outlook

6.1 Conclusion

In this work, a physical and mathematical model has been developed that enables the analysis of force development in *gunnun so ap joomuk kaunde baro ap jirugi* into *gunnun so ap joomuk kaunde baro ap jirugi* with a step and the corresponding wave.
To assess the exact influence of the wave on force conversion, the model analyzes individual components involved in the wave by isolating and examining the body's momentum with and without the wave, the force that can be generated by this momentum[11] as well as the vertical distance during the downward phase and its impact[12]. Additionally, the model can also generate and analyze scenarios of maximum force development.[13]
Since the model is implemented in the Python programming language, it allows for the automated investigation of any scenarios related to input parameters.

Due to the functionality described here, the model partly expands the understanding of the physical operation of the wave. Furthermore, it contributes to a better understanding of force generation in a technique in general. Therefore, it can serve as a valuable tool for Taekwon-Do teachers in training planning by providing an expanded understanding of techniques and forces.

Within this thesis, the following points for *gunnun so ap joomuk kaunde baro ap jirugi* in combination with a wave can be highlighted:

- up to approximately 1 % higher force values compared to an execution without a wave[14]
- the higher the horizontal total velocity of the body and fist, the less influence the wave has
- vertical distance is crucial
- the most effective execution of a technique along the resulting momentum (from top to diagonally down)

[11]See Chapter 5.2 starting from p. 17.
[12]See Chapter 5.3 starting from p. 19.
[13]See Chapter 5.4 starting from p. 19.
[14]See Chapter 5.1 starting from p. 16.

- higher force impact on the hip joint.[15][16]
- only limited suitability in the power breaking test

The model is, however, very rudimentary and only includes physical considerations regarding the wave in relation to the downward phase. Anatomical and physiological circumstances are not taken into account by the model. Examples of such include the fact that a muscle cannot contract arbitrarily fast and generate high force due to its friction. Furthermore, the input parameter values for the model are based on theoretical assumptions that are only partially supported by published data.

6.2 Outlook

For a more extensive validation of the model, further experiments are necessary in which data from different techniques with and without the wave are collected. In addition to validation, the model could be expanded and refined with such data, thus making it more aligned with reality. Furthermore, the relaxation and upward phases of the wave could also be considered in more detail.

A comprehensive model could furthermore be expanded through methods of artificial intelligence. The combination of established rules based on physical laws and learning algorithms could deepen the insights into Taekwon-Do techniques and principles for trainers, athletes, and other practitioners. This could potentially lead to more individualized execution of techniques, which could contribute to the maintenance of health and perhaps even the enhancement of the health of individual practitioners.

[15]See Chapter 5.2 starting from p. 17.
[16]For stresses on the hip joint in Taekwon-Do, see also Vanberghens, 2017.

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A Model

A.1 Calculations

Equation 17 shows the conversion from $\frac{\text{km}}{\text{h}}$ in $\frac{\text{m}}{\text{s}}$.

$$1\frac{km}{h} = 1000\frac{m}{h} = \frac{1000}{3600}\frac{m}{s} = \frac{1}{3.6}\frac{m}{s} \tag{17}$$

Equation 18 shows the calculation of the fist velocity.

$$80cm \Leftrightarrow 0.07sec \rightarrow \frac{80cm}{0.07} \Leftrightarrow \frac{0.07sec}{0.07} \rightarrow 1333cm \Leftrightarrow 1sec \rightarrow 13.33m \Leftrightarrow 1sec \tag{18}$$

A.2 Implementation

Listing 7: Implementation of the model with Python

```
import math

G = 9.81
MASS_EFFECTIVE_FACTOR = 0.5
ROUND_FACTOR = 2

def input_vertical_distance():
    return float(input(">- vertical distance (m): "))

def input_mass():
    return float(input(">- mass (kg): "))

def mass_effective(mass):
    return mass * MASS_EFFECTIVE_FACTOR

def input_velocity_body_wave():
    return float(input(">- velocity body wave (m/s): "))

def input_velocity_body_no_wave():
    return float(input(">- velocity body no wave (m/s): "))

def input_velocity_fist():
    return float(input(">- velocity fist (m/s): "))

def input_pulse_duration():
    return float(input(">- pulse duration (sec): "))

def vertical_velocity(vertical_distance):
    return math.sqrt(2 * G * vertical_distance)
```

```
def momentum(mass, velocity):
    return mass * velocity

def resultant(a, b):
    return math.sqrt(a ** 2 + b ** 2)

def print_horizontal_line():
    print("\n----------------------------------------")

def print_mark():
    print("\n########################################")

def print_anthropometry():
    print("\nAnthropometry")
    print("-> effective mass factor: {:.2f}".format(
       MASS_EFFECTIVE_FACTOR))
    print("-> effective mass: {:.2f} kg".format(
       mass_effective))

def print_wave():
    print("\nWave")
    print("-> velocity body vertical: {:.2f} m/s".format(
       vertical_velocity, ROUND_FACTOR))
    print("-> momentum body vertical: {:.2f} kg * m/s".format
       (momentum_body_vertical, ROUND_FACTOR))
    print("-> momentum body horizontal: {:.2f} kg * m/s".
       format(momentum_body_horizontal_wave, ROUND_FACTOR))
    print("-> momentum body: {:.2f} kg * m/s".format(
       momentum_body_wave, ROUND_FACTOR))
    print("-> force body: {:.2f} N".format(force_body_wave,
       ROUND_FACTOR))
    print("-> velocity total: {:.2f} m/s".format(
       velocity_total_wave, ROUND_FACTOR))
    print("-> momentum total: {:.2f} kg * m/s".format(
       momentum_total_wave, ROUND_FACTOR))
    print("-> force total: {:.2f} N".format(force_total_wave,
        ROUND_FACTOR))

def print_no_wave():
    print("\nNo Wave")
    print("-> momentum body: {:.2f} kg * m/s".format(
       momentum_body_no_wave, ROUND_FACTOR))
    print("-> force body: {:.2f} N".format(force_body_no_wave
       , ROUND_FACTOR))
    print("-> velocity total: {:.2f} m/s".format(
       velocity_total_no_wave, ROUND_FACTOR))
    print("-> momentum total: {:.2f} kg * m/s".format(
       momentum_total_no_wave, ROUND_FACTOR))
```

```
    print("-> force total: {:.2f} N".format(
       force_total_no_wave, ROUND_FACTOR))

def percentage(percentage_quotation, basic_value):
    return 100 - percentage_quotation/basic_value * 100

def print_comparison():
    print("\nComparison")
    if force_total_no_wave < force_total_wave:
        print("-> wave more force: {:.2f} %".format(
           percentage(force_total_no_wave, force_total_wave))
           )
    elif force_total_no_wave > force_total_wave:
        print("-> wave less force: {:.2f} %".format(
           percentage(force_total_wave, force_total_no_wave))
           )
    else:
        print("-> force generation is equal")

if __name__ == "__main__":  # Prevent execution during import
    print_mark()

    # input
    print("Input")
    vertical_distance = input_vertical_distance()
    mass = input_mass()
    velocity_body_wave = input_velocity_body_wave()
    velocity_body_no_wave = input_velocity_body_no_wave()
    velocity_fist = input_velocity_fist()
    pulse_duration = input_pulse_duration()

    # calculations
    mass_effective = mass_effective(mass)
    vertical_velocity = vertical_velocity(vertical_distance)
    momentum_body_vertical = momentum(mass_effective,
       vertical_velocity)
    momentum_body_horizontal_wave = momentum(mass_effective,
       velocity_body_wave)
    momentum_body_wave = resultant(momentum_body_vertical,
       momentum_body_horizontal_wave)
    force_body_wave = momentum_body_wave / pulse_duration
    velocity_horizontal_total_wave = velocity_body_wave +
       velocity_fist
    velocity_total_wave = resultant(vertical_velocity,
       velocity_horizontal_total_wave)
    momentum_total_wave = momentum(mass_effective,
       velocity_total_wave)
    force_total_wave = momentum_total_wave / pulse_duration
```

```
momentum_body_no_wave = momentum(mass_effective,
    velocity_body_no_wave)
force_body_no_wave = momentum_body_no_wave /
    pulse_duration
velocity_total_no_wave = velocity_body_no_wave +
    velocity_fist
momentum_total_no_wave = momentum(mass_effective,
    velocity_total_no_wave)
force_total_no_wave = momentum_total_no_wave /
    pulse_duration

# output
print_horizontal_line()
print_anthropometry()
print_horizontal_line()
print_wave()
print_horizontal_line()
print_no_wave()
print_horizontal_line()
print_comparison()

print_mark()
```

B Input and Output of Results

B.1 Greater Force Application

Listing 8: Greater force application, vertical distance = 0.15 m, mass = 110 kg

```
########################################
Input
>- vertical distance (m): 0.15
>- mass (kg): 110
>- velocity body wave (m/s): 1.4
>- velocity body no wave (m/s): 1.4
>- velocity fist (m/s): 10
>- pulse duration (sec): 0.1

----------------------------------------

Anthropometry
...

----------------------------------------

Wave
...
-> velocity total: 11.53 m/s
...
-> force total: 6340.60 N

----------------------------------------

No Wave
...

----------------------------------------

Comparison
-> wave more force: 1.11 %

########################################
```

Listing 9: Greater force application, vertical distance = 0.1 m, mass = 80 kg

```
########################################
Input
>- vertical distance (m): 0.1
>- mass (kg): 80
>- velocity body wave (m/s): 1.4
>- velocity body no wave (m/s): 1.4
```

```
>- velocity fist (m/s): 10
>- pulse duration (sec): 0.1

----------------------------------------

Anthropometry
...

----------------------------------------

Wave
...
-> velocity total: 11.49 m/s
...
-> force total: 4594.29 N

----------------------------------------

No Wave
...

----------------------------------------

Comparison
-> wave more force: 0.75 %

########################################
```

Listing 10: Greater force application, vertical distance = 0.05 m, mass = 50 kg

```
########################################
Input
>- vertical distance (m): 0.05
>- mass (kg): 50
...

----------------------------------------

Anthropometry
...

----------------------------------------

Wave
...
-> velocity total: 11.44 m/s
...
-> force total: 2860.74 N
```

```
----------------------------------------

No Wave
...

----------------------------------------

Comparison
-> wave more force: 0.38 %

########################################
```

B.2 Body Momentum and Transferred Force

Listing 11: Momentum and force of the body with and without wave, $\vec{v} = 0.8$

```
########################################
Input
>- vertical distance (m): 0.1
>- mass (kg): 80
>- velocity body wave (m/s): 0.8
>- velocity body no wave (m/s): 0.8
>- velocity fist (m/s): 10
>- pulse duration (sec): 0.1

----------------------------------------

Anthropometry
...

----------------------------------------

Wave
...
-> momentum body: 64.52 kg * m/s
-> force body: 645.23 N
...

----------------------------------------

No Wave
-> momentum body: 32.00 kg * m/s
-> force body: 320.00 N
...
```

```
----------------------------------------

Comparison
...

########################################
```

Listing 12: Momentum and force of the body with and without wave, $\vec{v} = 1.4$

```
########################################
Input
>- vertical distance (m): 0.1
>- mass (kg): 80
>- velocity body wave (m/s): 1.4
>- velocity body no wave (m/s): 1.4
>- velocity fist (m/s): 10
>- pulse duration (sec): 0.1

----------------------------------------

Anthropometry
...

----------------------------------------

Wave
...
-> momentum body: 79.22 kg * m/s
-> force body: 792.16 N
...

----------------------------------------

No Wave
-> momentum body: 56.00 kg * m/s
-> force body: 560.00 N
...

----------------------------------------

Comparison
...

########################################
```

B.3 Vertikal Distance

Listing 13: Importance of the vertical distance, vertical distance = 0.15 m

```
########################################
Input
>- vertical distance (m): 0.15
>- mass (kg): 80
>- velocity body wave (m/s): 1.4
>- velocity body no wave (m/s): 1.4
>- velocity fist (m/s): 10
>- pulse duration (sec): 0.1

----------------------------------------

Anthropometry
...

----------------------------------------

Wave
-> velocity body vertical: 1.72 m/s
...
-> velocity total: 11.53 m/s
...
-> force total: 4611.34 N

----------------------------------------

No Wave
...
-> velocity total: 11.40 m/s
...
-> force total: 4560.00 N

----------------------------------------

Comparison
-> wave more force: 1.11 %

########################################
```

Listing 14: Importance of the vertical distance, vertical distance = 0.1 m

```
########################################
Input
>- vertical distance (m): 0.1
>- mass (kg): 80
>- velocity body wave (m/s): 1.4
>- velocity body no wave (m/s): 1.4
>- velocity fist (m/s): 10
>- pulse duration (sec): 0.1
```

```
----------------------------------------

Anthropometry
...

----------------------------------------

Wave
-> velocity body vertical: 1.40 m/s
...
-> velocity total: 11.49 m/s
...
-> force total: 4594.29 N

----------------------------------------

No Wave
...
-> velocity total: 11.40 m/s
...
-> force total: 4560.00 N

----------------------------------------

Comparison
-> wave more force: 0.75 %

########################################
```

Listing 15: Importance of the vertical distance, vertical distance = 0.05 m

```
########################################
Input
>- vertical distance (m): 0.05
>- mass (kg): 80
>- velocity body wave (m/s): 1.4
>- velocity body no wave (m/s): 1.4
>- velocity fist (m/s): 10
>- pulse duration (sec): 0.1

----------------------------------------

Anthropometry
...

----------------------------------------

Wave
```

```
-> velocity body vertical: 0.99 m/s
...
-> velocity total: 11.44 m/s
...
-> force total: 4577.18 N

----------------------------------------

No Wave
...
-> velocity total: 11.40 m/s
...
-> force total: 4560.00 N

----------------------------------------

Comparison
-> wave more force: 0.38 %

########################################
```

B.4 Maximum Force Application

Listing 16: Maximum force application without wave, velocity body no wave = 2.2

```
########################################
Input
>- vertical distance (m): 0.1
>- mass (kg): 80
>- velocity body wave (m/s): 1.4
>- velocity body no wave (m/s): 2.2
>- velocity fist (m/s): 10
>- pulse duration (sec): 0.1

----------------------------------------

Anthropometry
...

----------------------------------------

Wave
...
-> velocity total: 11.49 m/s
...
-> force total: 4594.29 N
```

```
----------------------------------------

No Wave
...
-> velocity total: 12.20 m/s
...
-> force total: 4880.00 N

----------------------------------------

Comparison
-> wave less force: 5.85 %

########################################
```

Listing 17: Maximum force application without wave, velocity body no wave = 3.3

```
########################################
Input
>- vertical distance (m): 0.1
>- mass (kg): 80
>- velocity body wave (m/s): 1.4
>- velocity body no wave (m/s): 3.3
>- velocity fist (m/s): 10
>- pulse duration (sec): 0.1

----------------------------------------

Anthropometry
...

----------------------------------------

Wave
...
-> velocity total: 11.49 m/s
...
-> force total: 4594.29 N

----------------------------------------

No Wave
...
-> velocity total: 13.30 m/s
...
-> force total: 5320.00 N
```

```
----------------------------------------

Comparison
-> wave less force: 13.64 %

########################################
```

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