ANALYZING THE POTENTIAL TO COMBINE ENERGY GENERATING TECHNOLOGIES WITH STRENGTH TRAINING EXERCISE MACHINES

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Abstract

Our energy intensive lifestyle is damaging to ourselves and the environment. The developed world has established an intricate energy sector that is dependent on fossil fuels which relentlessly releases greenhouse gases into the atmosphere leading to climate altering impacts and environmental degradation. Americans, in particular, have used this development to become more sedentary and ultimately unhealthier. This research project is aimed at realizing the potential to electrify the fitness industry by examining the potential to make strength training exercise machines a distributed energy source. In this project, three designs were analyzed to understand their unique drivetrain components and how they operate. These designs include the SportsArt ECO-POWR G575R Recumbent Cycle, the NordicTrack Fusion CST, and Tonal. The research uncovered that there is a shift away from traditional, real weights to the use of magnetic resistance to provide the resistive force for cardio and strength training exercise machines. Interestingly, the magnetic resistance component allows for the designs to harness some of the mechanical energy from the user's workout and convert it to usable electricity; however, the electricity produced from this process was usually wasted as heat which raises the prospect of improving the design to capture that electricity. This research project found there was an adequate amount of potential to alter the designs of strength training machines to be net suppliers of electricity which could result in not only contributing to a healthier population, but this could also promote a more sustainable lifestyle.

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1. <u>Introduction</u>

One of the consequences to the evolution of our species has been a transition away from a physically active lifestyle. Before, energy needed to be conserved for necessities like finding a constant supply of food or carrying water from sources to shelters. Today, our lifestyles are considerably different compared to the lifestyles of our hunter-gather ancestors. According to Dr. Daniel Lieberman, “we have created a world in which we don’t need to do much work anymore” because we have developed an energy intensive network that offloads our need to be as physically active (NPR, 2021). While there are plenty of positive attributes linked to our developed world, there are some serious issues that must be resolved. Primarily, there has yet to be an adequate level of clean energy technologies installed to power this energy intensive network. Secondarily, record levels of obesity from a lack of enough physical activity has now plagued the health of millions of people across the world.

To sustain the current lifestyles of billions of people, fossil fuels are being consumed at an alarming rate. The result of excessively burning coal, natural gas, and oil is that for the first time since the Mid-Pliocene Warm period nearly 3.6 million years ago, the atmosphere has now peaked at carbon dioxide levels of 412.5 parts per million (Stein, 2021). The emissions from burning fossil fuels are directly contributing to elevated concentrations of greenhouse gases in our atmosphere giving rise to climate change and an unforeseen amount of expensive and potentially irreversible damage anticipated on each and every continent. Replacing fossil fuels with clean energy technologies has been a slow process, but continuous action will be necessary to avoid a “runaway greenhouse effect” in which positive feedback loops amplify unstable alterations to our planet (Archer, 2011). Although humans are solely responsible for this current climate crisis, a part of the solution could include harnessing the potential energy within the population itself by electrifying exercise equipment. Not only would this constitute as a source of clean energy, but it would also promote a healthier and more active lifestyle for people across the world.

The objective of this research project will be to review the designs and explain how different cardio and strength training machines work. And in doing so, potentially explore whether some of these designs suggest opportunities to convert some of the mechanical energy into electricity. There are a variety of different exercise machines that use either real weights, a dual motor-generator, or magnetic resistance techniques and some of these may be more suited to converting mechanical exercise energy into electricity than others.

2. Literature Review

Medical experts advise the same two cornerstones when guiding the general public to a healthier lifestyle: diet and exercise. Although exercising can be achieved through countless different physical activities, a popular option is to visit a gym where space, equipment, and trainers are available to support a variety of exercises. These dedicated facilities typically contain a diverse amount of exercise machines where people expend a considerable amount of energy using the equipment. Two of the most popular types of equipment found in gyms are cardio and strength training machines. Historically, these cardio machines have been designed with some form of brake and resistance whereas strength machines primarily used masses. Examples of common forms of cardio machines, or “endless-path machines” include treadmills, ellipticals, and stationary bikes (Zavadsky, 2012). In comparison, common strength training machines, or weight type devices, include barbells and weights with a “frame and bench assembly,” dumbbells, kettlebells, and weight stacks machines (Zavadsky, 2012).

More recently, there has been the adoption of implementing the use of electromagnetic induction to create resistance for use in strength training machines. While some of the more advanced cardio machines have been using electromagnetic induction to give users the control over the level of resistance, now strength training machines are using these same principles to simulate weight type devices. Two of the most popular designs that have incorporated electromagnetic induction into their strength training machines are NordicTrack Fusion CST and Tonal (NordicTrack, 2021 and Tonal, 2020). Usually, the energy generated with machines that use electromagnetic induction is wasted as heat, though some machines are considering ways to use work done to generate electricity that might be consumed directly by the machine or even stored and used externally. To date, SportsArt is the only patented supplier of exercise equipment that has realized the potential of capturing the kinetic energy of a user’s workout and converting it into utility grade electricity with their ECO-POWR line of cardio devices, though other suppliers often hint at the possibility of future designs capable of generating electricity, even where not implemented (SportsArt, 2020). Considering “gyms are traditionally large consumers of energy,” equipment that captures and converts the kinetic energy of both cardio and strength training machines into usable electricity could “offset electricity consumption” and contribute to a more sustainable vision (Zoet, 2020).

An integral part of this literature review includes a foundational understanding of magnetism and electrical generators. Because of the importance of this, the remainder of this literature review goes into a detailed understanding of magnetism, electromagnetic induction, linear generators, synchronous generators, supplemental power generation technologies, and energy storage technologies. The literature for the different exercise machines is not cited here because an analysis and discussion of these machines and their relevant patents, repair manuals, and available online documentation is included in the results section.

Electromagnetism

Electrical generation is a phenomenon that can occur from the interaction between electrical conductors and magnetic fields. A conductor is characterized as a material with "low resistance" which allows energy to travel through it with relative ease (Britannica, 2020). Metals are a prime example of a good conductor of both heat and electricity. For this reason, conductors are well suited for both the metal cooking pans that transports the heat of a flame to the food, as well as within transmission lines to allow the flow of electricity from a power plant to a residential unit. The role of a conductor can be fulfilled by a variety of elements on the periodic table, but copper is often chosen for its relatively affordable price and abundance on our planet.

Magnetic fields are associated with ferromagnetic materials like iron, cobalt, nickel, and other rare earth elements. It is within the atoms of these ferromagnetic materials that a magnetic field is created. Every element has at least one rotating, negatively charged electron around a positively charged proton in the nucleus, but it is in cases where atoms become ordered and have an unpaired electron that a net magnetic field may arise (Khan Academy, 2021). In contrast, materials whose atoms are disorganized with pairs of electrons, there is no net magnetic force. Although this magnetic force is not visible to the human eye, when a scattered pile of iron filings are placed on a piece of paper and held above a magnet, the ferromagnetic iron atoms in the filings become magnetically polarized and align themselves along the field lines of the bar magnet as depicted in Figure 1. Unlike the bar magnet, the iron filings are not permanently magnetized and so it is not until the magnetic field of the bar magnet intersects these iron filings that they become aligned. Thus, the magnetic field from the bar magnet induces the magnetism of the iron filings when in close proximity as shown below in Figure 1.

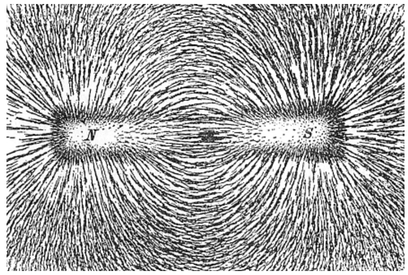


Figure 1 – Visual representation of the field lines of a ferromagnetic material using iron filings, paper, and a magnet. (Edison Tech Center, 2014).

An interesting relationship occurs when magnetic fields are altered in strength or physically moved through materials with good electrical conductivity. The physical phenomena that defines this interaction is known as electromagnetic induction, which is the "production of current in a conductor as it moves through a magnetic field" (Edison Tech Center, 2014). This current is a flow of negatively charged electrons under the influence of an electrical field which is more commonly referred to as electricity. To better understand electromagnetic induction, an explanation of Ampere's Law, Faraday's Law, and Lenz's Law will be provided below.

In the mid-1820's, Andre-Marie Ampere found that rather than using a magnet, another way of forming a magnetic field was through the flow of electrons in an electrical current. The magnetic field lines that are produced from this moving charge along a conductor behave just as the field lines of the bar magnet depicted in Figure 1 above. Although electrical fields behave in a similar manner as magnetic fields, the two are entirely separate forces. However, by observing the field lines, this provides a clear relationship between the electrical force and the magnetic force. As shown in Figure 2 below, when electricity is supplied to a conductor, this flow of electricity generates a radial magnetic field around the conductor. Just as the iron filings aligned themselves with the magnetic field of the bar magnet, the iron filings align themselves with the electrical field that emanates from the electrical current flowing through the coils of copper wire. Note that the iron filings furthest away from the coils are not aligned, whereas the iron filings closest to the coils clearly become organized around the magnetic field. This follows Ampere's Law which explains that the "magnetic field created by an electric current is proportional to the size of the electric current with a constant of proportionality" (Wood, 2015). This would imply that if more current were to be applied to the coil in Figure 2, the electric field would grow and unorganized filings would now align as magnetism is now being induced upon them. The strength of the magnetic field is directly related to the amount of current and the distance away from the coil. This is also the basis for how an electromagnet operates where the coils in Figure 2 would have a ferrous material like steel placed within coils to amplify the magnetic field.

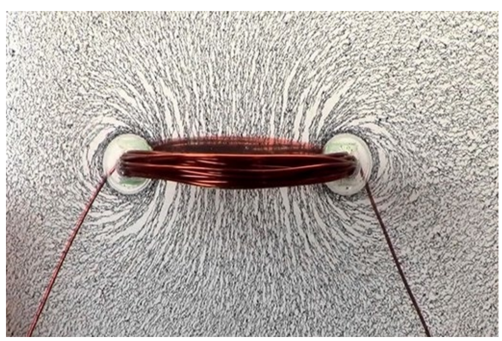


Figure 2 - Visual representation of the field lines from an electrical current using iron filings, a transparent sheet, and a coil of copper (Hadley, 2017).

Michael Faraday's experiments and research during the mid-1800s eventually became validified into what stands today as Faraday's Law of Induction, or more commonly referred to as just Faraday's Law. This law can be summarized as "(1) a changing magnetic field in a circuit induces an electromotive force in the circuit; and (2) the magnitude of the electromotive force equals the rate at which the flux of the magnetic field through the circuit changes" (Britannica, 2020). The electromotive force, or EMF, is a force that is measured in volts (V) which are a measure of energy per unit charge. It is this voltage that leads to an electrical field from the force of each unit of charge within the conductor. Additionally, this concept of magnetic flux is defined as a "measurement of the total magnetic field which passes through a given area," whereas a circuit is simply an enclosed pathway that allows electricity to flow (Khan Academy, 2021). An elementary form of a circuit could take the form of copper wire shaped into a loop, which is displayed in a description of Faraday's Law in Figure 3 below. Notice that the magnetic field lines from the bar magnet are not included in Figure 3; however, the radial magnetic field lines that Ampere first discovered from the electrons flowing through the circuit are present. In summary, Faraday's Law can be mathematically explained as the voltage equals the change in magnetic flux with time. This is otherwise stated by the formula $V = N \times \Delta\Phi/\Delta t$, where V is the voltage, N is the number of turns, or loops, of wire, $\Delta\Phi$ is the change in magnetic flux, and Δt is the change in time.

Figure 3 – A magnet passing through a loop of copper wire inducing electrons to flow counterclockwise through the circuit (Hershey, 2020)

Around the same time that Ampere and Faraday were researching electromagnetism, Heinrich Friedrich Emil Lenz was also making lasting contributions to this field. His research became a universally accepted scientific law in 1834 and is deduced by expanding on Faraday's Law (Britannica, 2020). Lenz's Law is an application of the conservation of energy and this law states that an "induced current produces a magnetic field that opposes the motions of the magnets" (Andrews, 2017). Lenz realized that because the act of pushing a bar magnet through a coil of copper induces electrons to flow through the coils and as these electrons flow they create radial electric fields around the coil causing them to behave as a magnet, or electromagnet, then there must be a force that opposes the act of pushing the bar magnet through the loop of wire. In other words, just as forcing the south poles of two magnets together repel one another, passing the south pole of a magnet through a coil of copper will induce "current flows in such a way as to make the side of the coil nearest the pole of the bar magnet itself a [south] pole to oppose the approaching bar magnet" (Britannica, 2020). Conversely, as the magnet is exiting out the other end of the coil of copper, the magnet and coil of copper will experience a force of attraction as seen in Figure 4 below.

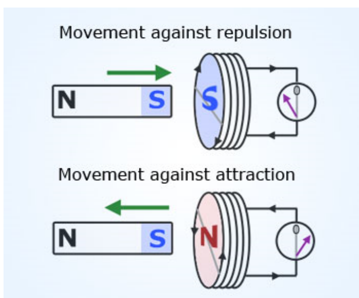


Figure 4 – Lenz's Law portraying the repulsion and attraction between a bar magnet moving through a coil of copper (Simply Science, 2018).

The key takeaway from these three laws explaining the relationship between magnetic fields and conductors is that by changing the magnetic flux through an electrical circuit, an electrical current is induced. The following section will provide a detailed explanation of linear generators and how they apply the principles of electromagnetism.

~~Linear Generators~~

~~The act of passing an individual magnet through a single loop of wire will only yield a nominal amount of electricity but scaling up this process can create one of the simplest forms of a generator. Otherwise known as a linear generator, these generators are an expansion of Figure 3 in the sense that they employ more magnets of increased strengths and pass them through more coils of copper. This basic design is explained below in Figure 5 where stacks of red and grey magnets are directed through green coils of copper. Although practical for specific applications, linear generators are infrequently used a significant source of power throughout our electric grid.~~

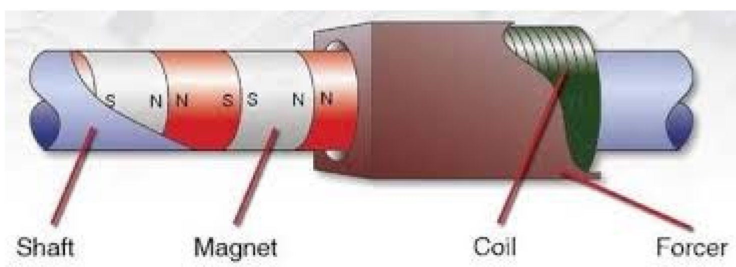
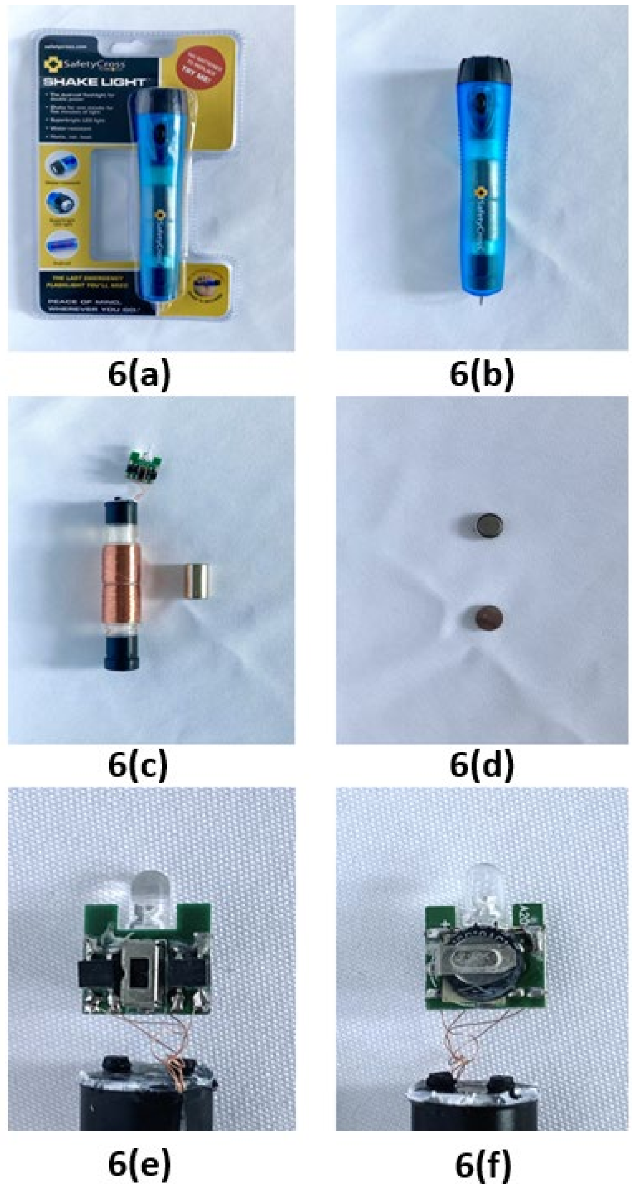


Figure 5– Components of a linear generator (Salman, 2012).

~~Linear generators are already commercially available in the form of a handheld device. A flashlight version, known as the Shake Light, converts the motion of a handshake directly into electrical energy by allowing a cylindrical magnet to move freely in a tube through coils of copper as seen in Figures 6(a) – 6(f) below. According to the manufacturer's specifications, the Shake Light can convert 60 seconds of continuous shaking motion into 300 seconds of lighting.~~



~~*Figure 4(a) – 4(e)* - Shake Light in package 6(a). Removed from package 6(b). Dissected view with interior magnet exposed 6(c). Exposed 5.5 V 0.33F capacitors 6(d). LED bulb attached to printed computer board and switch 6(e). Stacked capacitors fixed to printed computer board and LED bulb 6(f) (2021).~~

~~To get a better understanding of the design of the Shake Light, the protective housing, as indicated by the blue and black plastic case in Figure 6(a) and 6(b), was completed stripped away~~

to expose the skeleton of the linear generator in Figure 6(c). At the base of this skeleton is a black stopper with the sole purpose of keeping the magnet contained within the tube. Directly across the other end of the tube is another block stopper to not only contain the magnet, but also to protect the electrical and lighting components from making forceful contact with the sliding magnet. When the magnet is at rest at either end of the tube and in contact with the stopper, it is exactly one magnet's length distance away from the nearest copper coil. Connecting these two stoppers is a clear, thin, plastic tube with an inner diameter that is just slightly greater than the diameter of the magnet. Mounted around the plastic tube are two, identical, coils of copper wire. These coils are just slightly greater than the length of the magnet and are intentionally installed over the plastic tube to minimize the distance between the copper wires and the magnet. The magnet and coils of copper are deliberately arranged like this as to minimize any "wasted magnetic field out in the air" (Feynman, 2013). The result is an increased amount of electromagnetic induction because the magnetic field is greatest closer to the magnet, thus when the distance between the two are decreased, more change in magnetic flux will occur upon the coils of copper wire by the moving magnet.

The electricity produced from this handheld linear generator is transported by two wires from each coil and are directly connected to the lighting element's printed computer board. As indicated by Figure 6(e), one wire from each coil is directed to either side of the printed computer board, totaling two wires at either side. The microchip then begins feeding any induced current into two identical 5.5 V 0.33F capacitors, pictured at in Figure 6(d). These capacitors are stacked on top of one another and mounted to the microchip, as depicted in Figure 6(f). Once these capacitors have enough power stored, the user can flip the switch and begin transferring the stored electricity of the capacitors to the light emitting diode (LED) pictured in Figure 6(e).

~~The Shake Light does not use replaceable AA or AAA batteries that similar sized flashlights require. Alternatively, the design relies on capacitors connected to a linear generator which allows the user to never run out of a source of power for lighting considering the user has enough energy to shake the flashlight. This presents a clear tradeoff because these capacitors can only provide a limited supply of lighting for five minutes before depleting the stored electricity and demanding a recharge whereas traditional flashlights can provide a longer supply of lighting, but at the cost of occasionally requiring the user to replace the batteries. For this reason, the Shake Light caters towards emergency situations where there is a risk of batteries losing all charge without any available replacements, whereas traditional flashlights are more convenient for constant use with easily accessible battery replacements.~~

Synchronous Generators

Rather than rely on linear motion to drive a generator, Faraday opted to employ rotary motion when creating the first generator in 1831 (Paulus, 2018). Not only was this a more productive approach to generating electricity, but it was also a simpler way to generate electricity on a continuous basis. Figure 7 below portrays this rotary generator, also known as Faraday's Wheel, which featured a rotating copper disc between the magnetic field of two, fixed permanent magnets on either side (Paulus, 2018). By cranking on the handle directly attached to the shaft of the disc, Faraday's Wheel "successfully demonstrated electromagnetic induction," as currents were induced within the rotating copper disc. These currents, otherwise known as eddy currents, were characterized by low voltages that "tended to circulate backward and create counterflows," thus making the generator relatively impractical for power production (Paulus, 2018). These eddy currents create magnetic fields that resist the angular velocity and are comparative to a "viscous friction" acting against the rotation of the copper disc (Kirschner, 2010). While Faraday's Law of

Induction and Faraday’s Wheel were essential for the early stages of electrical generation, substantial advances were required to develop a generator that produced higher voltages.

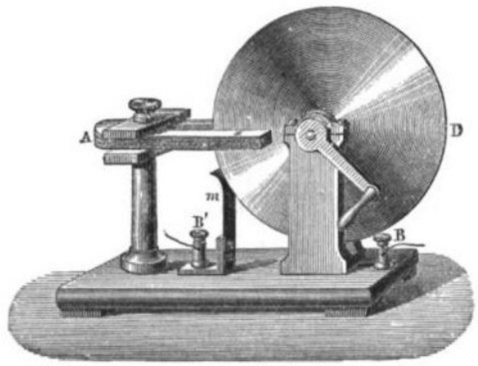


Figure 7 – Detailed sketch of Faraday’s Wheel (Paulus, 2018)

Faraday’s concept of using rotary motion to increase the amount of electromagnetic induction was revolutionary, but his design was inadequate for meaningful power production. It took a few decades for the engineering to advance, but in the early 1880s, Nikola Tesla developed his renowned “polyphase system” of alternating current technologies which gave rise to the first synchronous generators (Britannica, 2021). Through Tesla’s creativity, the field of electromagnetism perpetuated at such a rapid pace that within a few years August Haselwander developed the first three-phase synchronous generator in 1887 (Savaghebi, 2007). In 1891, Haselwander’s invention was displayed on the world stage as the “first large-scale demonstration” of generating alternating current from a synchronous generator. Klempner, 2004). Figure 8 below features the exact generator Haselwander used to transmit alternating current approximately 110 miles from Lauffen, Germany to the international electrical exhibition in Frankfurt, Germany (Klempner, 2004).

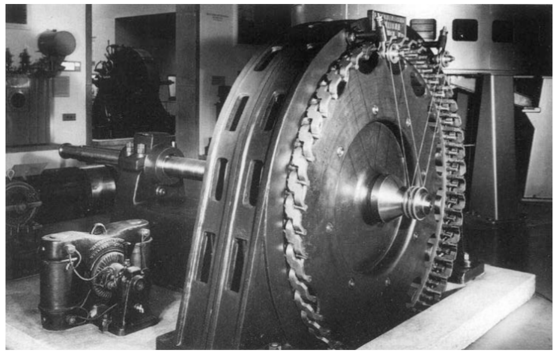
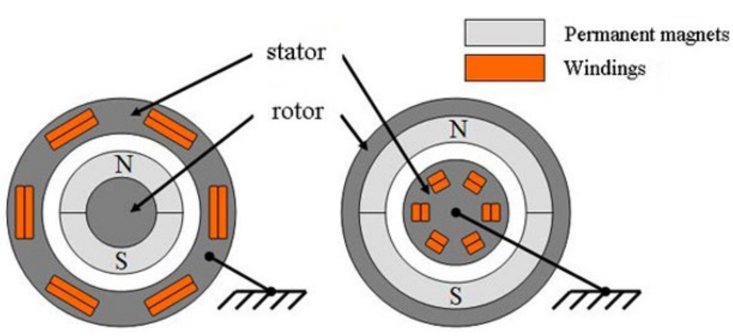


Figure 8 - August Haselwander's synchronous generator. (Klempner, 2004).

Synchronous generators, much like Faraday's Wheel, employs rotary motion and electromagnetic induction; however, the advanced design relies upon dedicated rotors and stators. The rotor of the generator is the rotational element, much like the rotating conducting disk of copper labeled "D" in Figure 7 above. Alternatively, the stator is the stationary element of the generator, much like the fixed permanent magnets labeled "A" in Figure 7 above. Although there are clear similarities between the interaction of conductors and magnetic fields for Faraday's Wheel and synchronous generators, there are significant differences in the design including where electromagnetic induction occurs. One notable difference is that the generated electricity from a synchronous generator is available for external use rather than wasted as heat from the induced eddy currents in Faraday's Wheel.

The most significant difference is that the current is induced in the rotating disc of Faraday's Wheel while it is generated in the stationary loops of the copper wires in a synchronous generator. In both cases the electrical current and associated magnetic field induced is due to a change in magnetic flux in relation to time through the metal wheel or wires. However, the change in the magnetic flux is achieved for Faraday's Wheel by rotating the metal wheel relative to a fixed magnetic field and for the synchronous generator by rotating the magnet and associated magnetic field relative to the fixed wires.

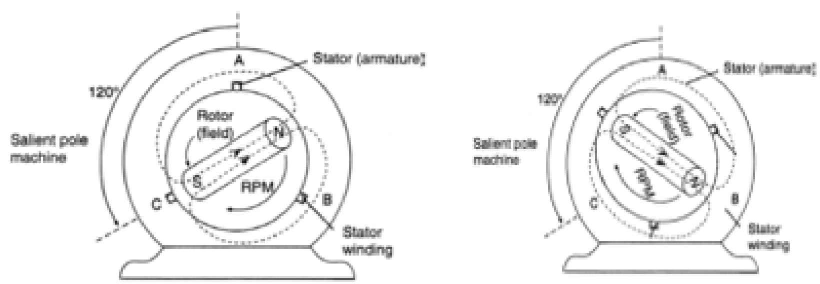
Another notable difference is that there is a substantial increase in the surface area of the interactions between the magnetic fields and the conductors. This design allows the stator to completely encompass the rotor which allows the conductors and magnetic fields to be constantly interacting when the rotor is in motion, thus there is greater magnetic flux available to induce a current within the conductor. The conductor in Figure 9 below is labeled as a winding which are tightly wound coils of copper usually wrapped around iron cores. A winding inherently acts as more advanced circuit with more loops of wire that will increase the flow of electrons compared to a single loop of wire. Figure 9 depicts the two styles of synchronous generators, both of which are characterized by keeping the conductor in a fixed location while rotating the magnetic field. Figure 9(a) involves a stator of copper windings around a rotor of permanent magnets while Figure 9(b) includes a rotor of permanent magnets around a stator of copper windings. Additionally, these permanent magnets can be substituted for electromagnets. These electromagnets are essentially windings, but they are designed to have current supplied through the coils of copper which will then make the iron core behave “similarly to a permanent magnet” with the exception that “the magnetism will practically disappear upon the discontinuation of the electric current through the wire” (Underhill, 1910).



9(a) 9(b)

Figures 9(a) and 9(b) - cross sectional view of two versions of a synchronous generator (EON Market Research, 2020).

One of the most important design features of today’s synchronous generators is they generate poly-phase, or three-phase power. This is achieved by offsetting three sets of copper windings by one-hundred and twenty degrees from one another so that the supply of voltage and current induced in each winding will be equally out of phase from another as the magnetic field rotates. This is apparent in Figure 10(a) below which portrays no magnetic field lines interacting with the stator windings at location C, whereas the stator windings positioned at locations A and B are supplying a current from the changing magnetic flux that intersects their location.

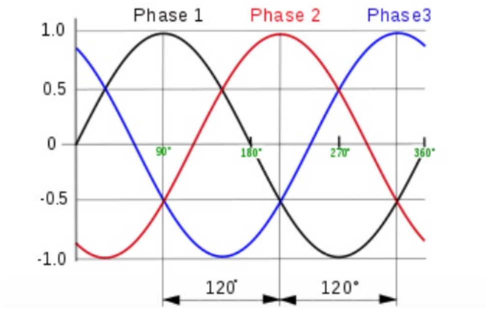


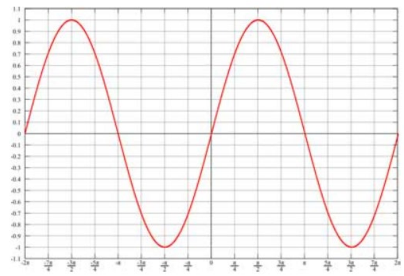
10(a) 10(b)

Figures 10(a) and 10(b) – Diagram of offset stator windings to provide three-phase current (Klempner, 2004).

In comparison, Figure 10(b) depicts the impact that a rotating magnetic field would have on the current supplied by this synchronous generator. Now that the North pole of the magnetic field produced by the rotor is directly pointed at the location of the copper windings at location B, there are no magnetic field lines intersecting this section of the stator and there will be no current induced at location B. Although location B is no longer supplying current when the rotor's magnetic field is in this position, the electromagnetic induction occurring at the stator windings at location A and C allow this synchronous generator to maintain a steady supply of current because the magnetic field lines are interacting with the stator windings at these two locations.

This cycle of one location of the stator windings producing no current at all while the other two locations maintaining a variable supply continues with each revolution of the rotor. Figure 11(a) below portrays this sinusoidal cycle of alternating current (AC) that occurs at each stator winding location as the magnetic field rotates. Each stator location is marked with a different color and is out of phase with one another by exactly one-hundred and twenty degrees. Figure 11(a) clearly shows how there will always be a steady supply of current because the offsetting of stator windings allows the interaction between the conductors and magnetic fields to remain in balance. The alternative approach is shown in Figure 11(b) which represents a generator that does not employ this pattern of offset stator windings. This design is known as single-phase and creates electricity characterized by spikes and drop offs as the rotating magnetic field provides an unsteady and unbalanced supply of current. For this reason, single-phase generators can only be functional in situations that require lower electricity demands such as "lighting and heating, and for small electric motors," but are "unusual for power ratings above 10kW" (Tecnis Carpi, 2017).





11(a) 11(b)

Figures 11(a) and 11(b) – Mathematical representation of current supplied by a three-phase 11(a) and single-phase 11(b) generators. (Tecnics Carpi, 2017).

Additional Technologies to Supplement Power Generation

The supply side of producing electricity from generators is relatively straightforward, but the demand side of consuming electricity can be much more complicated. There are a vast amount of different types of electrical devices available on the market, but each of these devices usually requires a specific amount of voltage, frequency, and current to operate. The following sections will provide a brief explanation to the types of technologies that may be required to supplement power generation equipment.

The production of alternating current (AC) from a synchronous generator is extremely common throughout our energy sector, but another option is to produce direct current (DC) from a DC generator. Both styles of generators have their own unique advantages, but the technologies and appliances in our homes have been standardized to operate on AC. For this reason, if a DC generator is used, the produced DC current must be rectified to AC current through an inverter. Another important role of an inverter is to regulate the current that is produced by a generator. The North American grid is designed to operate at sixty Hertz (Hz); thus, most appliances also require sixty Hz to function properly. For this reason, any electricity produced by a generator that is not at or near sixty Hz will require some form of rectification. Inverters are used in this instance to maintain the power along electric grid as close to 60 Hz as possible.

Inverters are commonly found in rooftop solar installations because photovoltaics are a unique type of DC generator that produce DC current which must be rectified to AC current before it is consumed on site. The technicalities of an inverter are described later in this project, but the basic concept is to take an input source of DC power and convert it to AC power as seen in Figure 12 below. The two types of inverters that dominate the market are microinverters and macroinverters. The difference between the two are that a single macroinverter is used to invert the DC current from multiple photovoltaic (PV) panels whereas a single microinverter can be used to invert the DC current from an individual PV panel.

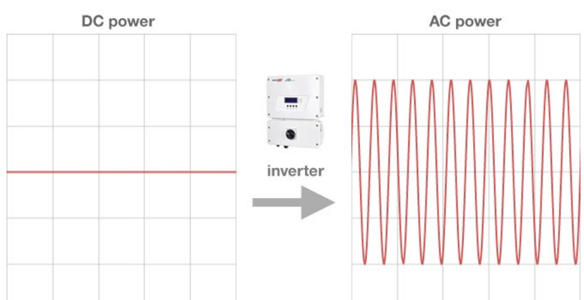


Figure 12 – An inverter's role of rectifying supplied DC power into grid quality AC power (The Solar Nerd, 2020).

In the event that a generator is not rotating fast enough for adequate power production, a gearbox could then be implemented to increase the revolutions per minute. Gearboxes are common in wind turbines because the rotational speed of the generator is dependent on the wind at any given moment. To account for the variable nature of wind speeds, a gearbox can be installed so that even low wind speeds can produce a viable amount of electricity by the wind turbine.

Generally, the main reason to include a gearbox into any system is to “multiply torque and/or friction, divide speed, and or split power” (Valente, 2019). Figure 13 below is an example of a gearbox that could utilize slower speeds and higher torques at the input shaft. Through a precisely designed set of gears with different sizes and ratios, a gearbox can increase the revolutions per minute (rpms) at the output shaft. The result is a greater change in magnetic flux from more electricity production from the increase in rpms, but at the cost of translating the higher torque at the input shaft for lower torque at the output shaft. While not commonly found in strength training machines, Tonal includes a gearbox in one proposed version to support the “relationship between tension and torque” of the cable around the motor (Orady, 2020). Additionally, some cardio machines implement gearboxes to adjust the speed for optimal user experience by reducing the risk of injury as well as minimizing noise (Zhaowei, n.d.).

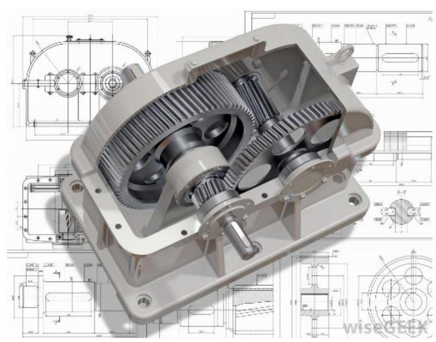


Figure 11 – Gearbox with top housing removed to expose the gears and shafts (Francois, 2021).

Throughout the process of electricity production, power management is usually required to keep the system operating in optimal condition. Printed circuit boards (PCBs) can be integrated into electronic systems to achieve power management through a complex system of interconnected “semiconductors, connectors, resistors, diodes, capacitors, and radio devices” (Printed Circuits, 2021). Different combinations of these components together on an interactive plate of circuits allows different currents, signals, and voltages to flow within the system and fulfill an expansive role of functions. In cardio exercise equipment, the functions of the PCBs usually entail illuminating the display panel to indicate a user's heart rate, distance traveled, and speed of the user. In some strength training exercise equipment, PCBs are being used to control the amount of current sent to an electromagnet or to alter the position of a moveable magnetic component relative to a conductive flywheel to change the resistance level experienced by the user.

PCBs have advanced power systems by increasing the efficiency of generators, prolonging the lifespan of the equipment, as well as providing vital safety features. Common types PCBs in power generation include, but are not limited to drive boards, power boards, control boards, and display boards. The intricacies that detail the operation of the variety of these computer boards is beyond the scope of this paper; however, the important takeaway is that power generation can be complemented with the addition of computer hardware. Figure 14 is included below as an example of a drive board installed downstream from a generator to provide power management for the SportsArt ECO-POWR G575R Recumbent Cycle cardio machine

Figure 14 – Exposed view of the drive board used in the SportsArt ECOPOWR G575r Recumbent Cycle (SportsArt, n.d.).

Different Forms of Storing Electricity

In most exercise machines that use electromagnetic resistance the energy is wasted as heat or in some cases may be used to provide limited electrical power to the machine. This raises a broader question of whether the work done and electricity generated by some machines could be designed to provide external power. However, because the power generation output may vary, it may be useful to first store the energy. Figure 15 below is included to portray some of the storage technologies discussed below and how they compare when relating the amount of energy storage capacity in comparison to the rate at which the energy storage is released.

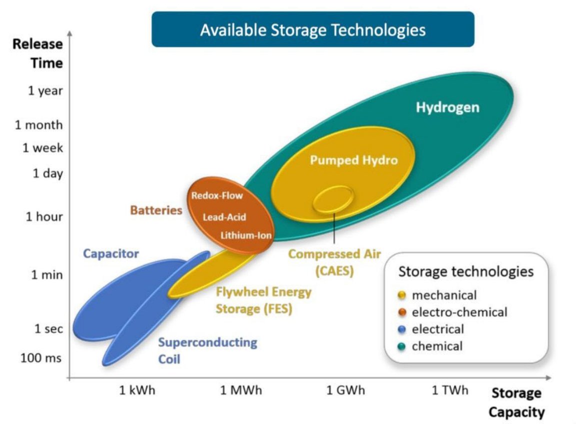


Figure 15 – Storage Capacity vs Release Time of a variety of available storage technologies. (Joi Scientific, 2021).

Flywheels are a form of energy storage that use kinetic energy to store electricity. In their most elementary form, "a flywheel is a disk with a certain amount of mass that can spin" (Gao, 2015). Once the disk is motion, the flywheel can now provide "frequency regulation and electricity quality improvements" by smoothing out any irregularities from the input source (Energy Storage Association, 2020). Flywheels are also versatile in the sense that they can mounted on a shaft with a rotor and stator and, depending on the system's current state of need, can behave as either a motor or generator as seen in the flywheel energy storage system of Figure 16 below.

In times of excess electricity, supplying these types of flywheels with a current through the stator will force the rotor to rotate and the system will function like a motor and the flywheel will begin spinning to store electricity in its rotating mass. When there is a deficient amount of power, this revolving flywheel can then serve the function of a generator by keeping the rotor in motion and causing it to induce a current in the stator to become a supply of electricity, just like the synchronous generator previously described. The benefit of the stored energy of a flywheel is that it is available immediately, which also means they are also not commonly characterized as long-term source of storage. Flywheels are also a key component in cardio exercise machines as they can smooth out the irregular pedaling motion of the user. In addition, when equipped with an electromagnetic resistance component, flywheels can perform the function of applying a controllable amount of resistance against the user. This process has even been adopted into strength training machines which will be discussed later on when explaining the NordicTrack Fusion CST.

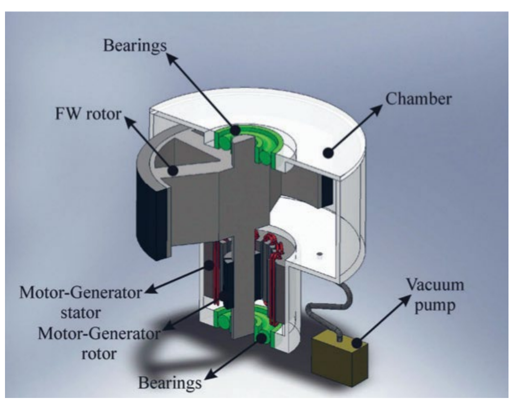


Figure 16 – Flywheel energy storage system diagram (Goncalves de Oliveira, 2011).

Capacitors store energy in a different manner and are useful when power is needed for a short period of time. Rather than rely on kinetic energy to store electricity, capacitors store electrons in an “electric field” to be used when a burst of power is required for a relatively short period of time (Evans, 2019). While a short-term supply of electricity may not initially appear worthwhile, the role of capacitors has made electronic systems operate at a higher level of efficiency. When supplied power, capacitors will begin storing a limited amount of electrons in an electric field without interrupting the flow of current in the circuit. In the event that power is then reduced or stopped completely, a capacitor begins discharging the stored electrons instantaneously to maintain a steady supply of current in the circuit. This basic, yet necessary function of “storing and smoothing out electrical energy” has been found to be widely applicable for handheld devices as well as large electrical grid operations (Powers, 2015). The integration of capacitors in electronics is highlighted in Figure 14 above as they are characterized by the cylindrical components extending outwards from the printed circuit board.

One of the more creative solutions to storing electricity for a longer period of time comes in the form of thermal storage. One type of thermal storage involves using an excess of electricity to create a stockpile of ice that will then be repurposed to complement a building’s air conditioning system. Ice Energy, an industry leader in thermal storage, developed the Ice Bear to shift electrical loads by capitalizing on affordable, off-peak electricity to create a block of ice within a well-insulated enclosure. The Ice Bear, as seen in Figure 17, is engineered to be installed in tandem with traditional air conditioning units, where this block of ice replaces the role of the condenser during peak hours of use. In traditional air conditioning systems, the condenser is notoriously energy intensive, yet it is essential because it performs the role of a heat exchanger for the refrigerant. Temporarily diverting the refrigerant away from the condenser and through the block of ice provides the same necessary heat exchanging function, yet only requires a fraction of the energy. Once the block of ice has completely melted, the refrigerant is redirected back into the condenser. Although the Ice Bear was initially designed to shift peak loads to overnight hours, a building that has the capability to be a net supplier of energy could continuously power the Ice Bear to maintain the block of ice and replace the role of the condenser altogether (Hopkins, 2021). A building could become a net supplier of energy through a rooftop solar system, or hypothetically, from a facility with enough energy generating exercise machines.

Figure 17– Ice Energy with tank exposed to reveal block of ice (Designer Pages Media, 2016).

The form of energy storage currently receiving the most attention would arguably be the Lithium ion technologies due to their rapidly growing use in the transportation sector, and more recently to support the integration of more renewable energy into our electric grid. Lithium ion (Li^+) is similar to the first battery created by Alessandro Volta back in the early 1800s with the main difference being the chemical construct. These batteries are intentionally designed to have an electrical current applied to the device which causes a reverse chemical reaction to occur inside the battery that would not have occurred under ordinary circumstances. The battery delivers the stored energy by allowing the normal, or forward, reaction to occur when desired, thus returning some of the energy in the form of usable electricity. The battery is able to provide electricity because it gives back energy that the reaction initially received when forced to run in reverse while the battery was being charged. In summary, by charging a battery, electricity is needed to make a chemical reaction go in reverse whereas discharging allows the normal chemical reaction to occur which releases the stored energy that was originally supplied to the battery.

The discovery that a flow of Lithium ions within a network of materials can force electrons to flow through an external circuit has been widely recognized as revolutionary technological advancement. The team that developed this technology were awarded the Nobel Prize in Chemistry in 2019 (Liu, 2019). John B. Goodenough, M. Stanley Whittingham, and Akira Yoshino were the scientists that are responsible for this technology that has resulted in propelling the electrification of vehicles while simultaneously providing clean energy installments the advantage of flexibility and reliability. Chemical storage in the form of Lead Acid batteries had previously been the standard for automobiles, but from Figure 18, it is clear that Lithium ion batteries are characterized by a significantly higher energy density than other chemical storage options. This higher energy density has allowed Lithium ion battery cells to dominate in recent years while also driving down their cost as economies of scale are realized.

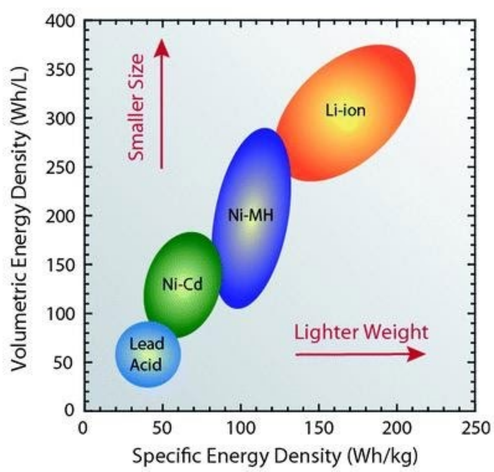


Figure 18 - Specific Energy Density plotted against volumetric energy density for a variety of chemical storage technologies (Epec, 2021).

3. **Methods**

To gain an understanding of the current state of the exercise industry and the potential to integrate energy generation into strength training machines, the following procedure was followed. The research and analysis of different types of rotary cardio and strength training machines in this report is broken down into five parts, plus a discussion section.

Part one includes a review of an advanced braking mechanism known as magnetic resistance and how it is used in some exercise equipment. Part two involves a detailed look at different SportsArt Recumbent Cycles that use magnetic resistance and how the design varies depending on whether or not the energy generated by the rider is wasted as heat or converted to electricity. Part three contains an analysis and discussion of strength training and the principles of operation using a mass-based design in weight stack machines. Part four consists of a description of the NordicTrack Fusion CST which is a new class of exercise machine that uses magnetic resistance to allow the user to perform both cardio and strength training at the same time. Part five includes a detailed evaluation of Tonal which is a strength training machine that uses artificial intelligence to simulate mass based weights through electromagnetic resistance.

These in-depth evaluations included analysis of the unique components and drivetrain technologies as well as an explanation of how to properly operate the following machines. This research often required a detailed review of patents, repair manuals, user manuals, and other various forms of online literature because consistent and reliable information about the machines was not publicly available. Therefore, a substantive part of this analysis is embedded within the results section to address the hypothesis. In order to recognize which designs suggest opportunities to convert some of the mechanical energy into electricity involved simply understanding and explaining how the machines currently work. The level of detailed analysis in the results section is why the patent, repair manual, owner manual, and other various forms of online literature is in this section rather than the literature review.

In the discussion section, a comparison of the NordicTrack Fusion CST and Tonal is conducted to understand the advantages and disadvantages of each of these strength training machines. The strengths and weaknesses of these two designs is then taken under consideration to propose a strength training design with a goal of net power production. The role that this proposed strength training machine could fulfill is then emphasized by suggesting how these machines could be strategically implemented within our carbon-constrained society.

4. Results

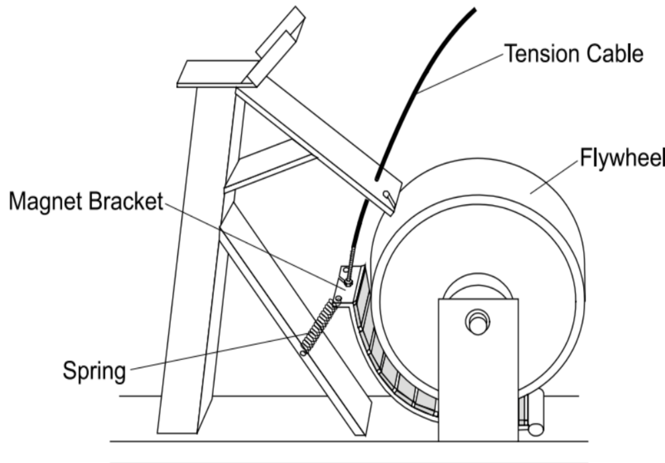
This section is divided into five parts as outlined in the methodology and all this material is intended to support the analysis of how machines that use magnetic resistance or other techniques such as motors might be able to better utilize the energy to provide electricity for external use. For some designs, this may not be possible, and we also consider how designs may be modified in some cases.

To do this, we need to understand how these machines work in some detail and that is often not obvious from the available literature. For this reason, a substantive part of this results section is an analysis of what is in patent information, manuals, and other online sources to better understand how these machines work so that the potential to propose modified designs can be discussed.

Part I: Introduction to Magnetic Resistance Exercise Machines

Cardio training is a specific style of exercising that focuses on improving the cardiopulmonary system. These types of workouts are characterized by “long-term repetitive uses of non-specific large muscles groups” which target the blood and oxygen circulatory systems (Zavadsky, 2012). The equipment designed specifically for cardio, or aerobic, exercises come in a variety of designs which commonly includes: treadmills, stationary bikes, ellipticals, or variations of these. Interestingly enough, the majority of these cardio machines employ some of the power generation technologies previously discussed. Treadmills, for example, draw electricity which is then used to make a motor’s rotor rotate and drive a conveyor belt at a variety of speeds in which a user can walk, jog, run, or even sprint. Alternatively, stationary bikes use flywheels of varying weights and sizes that are designed to simulate the experience of riding a bicycle. As aforementioned, this is in addition to smoothing out any irregular motion of the user.

A feature of some designs of cardio equipment is the use of magnetic resistance. This magnetic resistance is in fact resistance due to electrical currents induced by changing magnetic flux from either a permanent magnet or an electromagnet through a conductor. Not to be confused with the resistance characteristic of conductors, rather magnetic resistance uses the strength of a magnetic field and the resulting opposing force from the induced current from a changing magnetic flux to impose resistance against the user for a more strenuous exercise. Figure 19 below illustrates this function of magnetic resistance that allows a user to control the amount of resistance experienced by changing the distance between a magnet bracket and a flywheel constructed out of conductive elements.



Figures 19 - Example of magnetic resistance in exercise equipment (Teeter, 2021).

An explanation of the resistance that these flywheels generate resembles the same resistance that occurred in the earlier description of Faraday's Wheel. In Figure 19 above, the interaction between the adjustable magnet bracket and the conducting flywheel would be at its highest when the gap between the magnet bracket and flywheel is smallest because the rate of change of magnetic flux through the flywheel's metal rim will be the greatest for any given speed of rotation of the flywheel. Just as the coils of copper emitted a radial magnetic field that opposed the magnetic field of the approaching bar magnet in the scenario describing Lenz's Law in Figure 4 above, the rotating flywheel will also emit a magnetic field that opposes the applied magnetic field from the magnet bracket. The flywheel is not necessary copper like Faraday's Wheel; however, by using a metal or alloy with high electrical conductivity in this flywheel, an increase in eddy currents will be induced within the flywheel as the magnet bracket moves closer. Just like in Faraday's wheel, the impact of the magnetic field created by these eddy currents are equivalent to "viscous friction" that oppose the rotation of the flywheel (Kirschner, 2010).

Control over the position of the magnet bracket can be accomplished in the simplest designs through a knob directly coupled to the tension cable that the user must tighten or loosen. In doing so, tension on the cable is either increased or released, resulting in the magnet bracket moving closer or further away from the flywheel. Alternatively, the more sophisticated designs only require that the user selects a resistance level by pressing a button which then commands a motor to increase or release the tension on the cable. The lowest level of resistance is achieved when all the tension is relieved from the tension cable and the attached spring. At this point the user will be required to exert less energy to begin rotating the flywheel and maintain its rotational motion. This is when the magnetic field of the bracket is at its furthest distance away from the flywheel and the induced eddy currents are minimal. The less eddy currents induced in the flywheel, the less forces acting against the rotation of the flywheel and the easier it is for the user to keep the flywheel in motion. To exemplify the similarities between magnetic resistance flywheels and Faraday's wheel, Figure 20 is included below. Note this design does not use a magnet bracket that parallels the curvature of the flywheel like in Figure 19 above, rather two, fixed permanent magnets on either side of the flywheel are used to achieve the same resistance effect.

The question this raises is could this energy that is wasted in eddy currents to produce magnetic resistance be better utilized for electricity production. In the next section we discuss the SportsArt ECO-POWR line of equipment where the produced currents are converted to usable electricity to be consumed on-site.

Figure 20 – Magnetic resistance of stationary bicycle with a similar structure of Faraday's Wheel (Eaton, 2020).

Part II: SportsArt ECO-POWR

SportsArt is currently the only commercially available, patented exercise equipment manufacturer with products that are designed to capture the kinetic energy of a user's workout and convert it into usable electricity. After decades of knowledge and experience in the fitness industry, SportsArt took their company in a sustainable direction with their recently developed ECO-POWR line. Although none of the machines in Figure 21 below qualify as strength training equipment, an analysis of SportsArt ECO-POWR (SportsArt EP) is included below to gain an understanding of how existing exercise machines that also use electromagnetic induction have accomplished net power production at a competitive cost.

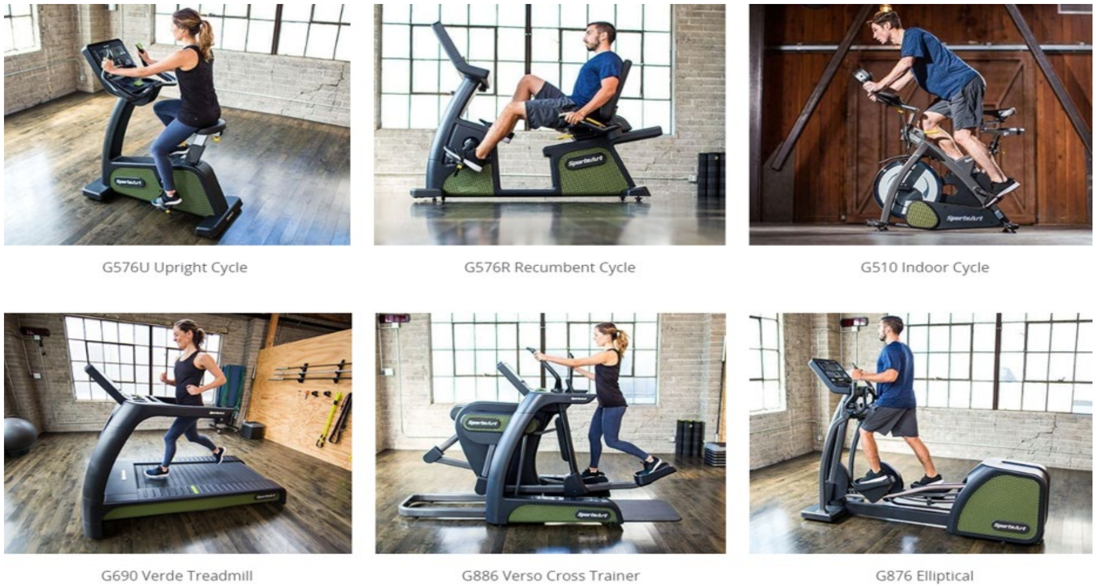


Figure 21 – SportsArt's ECO-POWR line of energy converting cardio machines (SportsArt, 2020).

While each of the models in Figure 21 above have power producing capabilities, only an explanation will be provided on the G575R Recumbent Cycle highlighted in Figure 22 below. This model was selected not only because of the familiarity of bicycles throughout the world, but also due to the accessibility of credible documentation. Another justification for explaining the G575R is that its design is consistent with four of the six machines featured in Figure 21 above. Only the G690 Verde Treadmill operates differently than the five other designs above and is beyond the scope of this Capstone.

The following sections will begin by explaining the major similarities and differences between traditional, non-power producing Recumbent Cycles and the G575R Recumbent Cycle, followed by a description of how the machine is operated, and concluded with an analysis of the drive train components featured in this SportsArt EP model shown in Figure 22 below.

Figure 22 - SportsArt ECO-POWR G575R Recumbent Cycle on the left alongside traditional SportsArt C55R Recumbent Cycle on the right (SportsArt, n.d. and SportsArt, 2021)

Just by examining the outward appearance, there would appear to be plenty in common between traditional, non-power producing RC's and the SportsArt EP RC; however, there are a variety of similarities underneath the protective housing as well. Exposing the innerworkings of both types of RC's would reveal that flywheels, power boards, drive belts, and alternators are included in the SportsArt EP RC design as well as most traditional RC's (Arriza, 2017).

For consistency, an alternator is a specific term for a synchronous generator that converts mechanical energy into alternating current by forcing a magnetic rotor to rotate within stator windings. For the SportsArt EP RC, the mechanical energy forcing the rotor of the alternator to rotate is the pedaling of the user which creates a change in magnetic flux within the stator and resulting in electromagnetic induction to occur. Because traditional RC's are forcing this magnetic rotor to spin within a stator, the induced current is actively shed, rather than converted to usable electricity. Some ways that traditional RC's are able to shed this energy is through heat and friction. Thus, the major difference that allows SportsArt EP's RC design to harness the kinetic energy of a user's workout is through the inclusion of a microinverter. This process is efficient not only because it harnesses energy that would have otherwise contributed to heating the room, but also because the result of this outcome is a modest amount of usable electricity. Early models of the SportsArt EP line required a separate “booster box” that housed the inverter and required a licensed professional to install, but with advances in technology and engineering, all the components now safely fit within the housing of the machine in a user friendly “plug and play style” (Arriza, 2020). Rather than use an energy storage technology for the surplus generated electricity, this microinverter design allows any produced electricity to flow directly to the circuit box of the facility to then be consumed on site.

One notable difference between an ordinary bicycle and a RC is that the change in seating does require the pedals to be positioned in front of the user, but this is only to offer the user a more comfortable seat with spinal support. Thus, there is a negligible difference between the operation of an RC and an ordinary bicycle. To operate the SportsArt EP RC, the user must become seated with both feet strapped into the pedals. The user can now begin “rotating a crank” through the pedaling motion driven by their lower body (Chen, 2003).

As pictured in Figure 23 below, because the pedal and crank are bolted to the drive pulley assembly, as the user pedals, the rotational kinetic energy is transferred to the flywheel through the drive belt. This drive belt is meant to serve a similar function that a chain has on regular bicycles, except these are composed of durable “rubberized fabrics” and require “high tension” to transmit rotational energy through friction (Foszcz, 2001). Just like the flywheel energy storage system explained in Figure 16 above, this flywheel requires a certain amount of energy to be put into motion. In these exercise machines, this is accomplished by transferring the rotational motion of the pedaling from the drive pulley assembly to the flywheel through the drive belt.

Because this pedaling motion can be jerky and erratic, the flywheel also serves a necessary function of smoothing out this unsteady motion before it reaches the alternator.

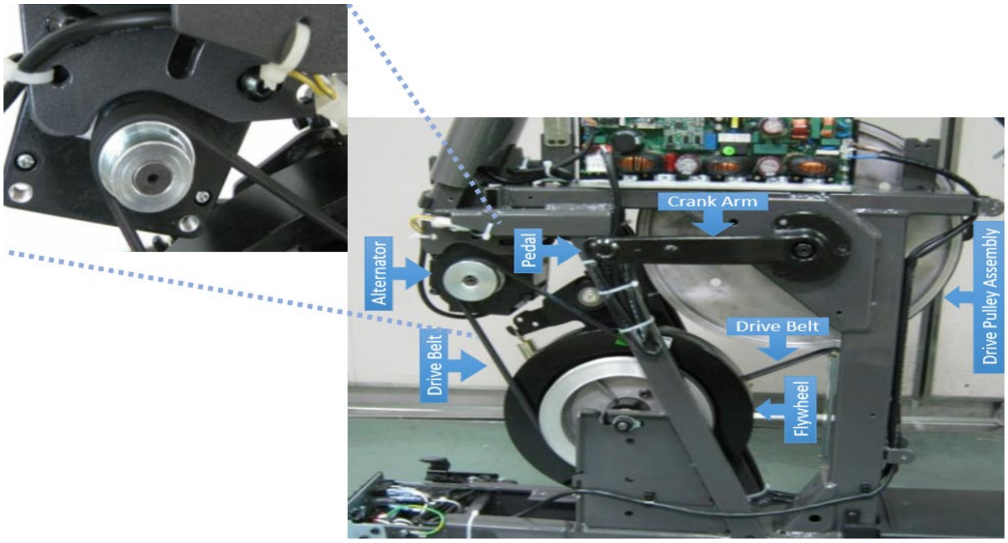


Figure 23 – SportsArt ECO-POWR G575 Recumbent Cycle with protective housing removed to expose interior components with generator highlighted (SportsArt, n.d.).

Just as the drive belt attached between the drive pulley system and the flywheel is used to transmit rotational energy, a second drive belt is used to transmit rotational energy between the flywheel and the alternator. The zoomed in view at the top of Figure 23 above shows the tension that the drives belts are under to achieve minimal power losses. According to Foczyz, the efficiency of flat drive belts are around 99%, thus only 2% of the energy initially supplied to the pedals is lost by the drive belts before reaching the alternator (2001). This rotational energy is delivered directly to the magnetic rotor because the rotor is coupled to the shaft of the alternator. Much like the design in Figure 9(a) above, this magnetic rotor will be forced to rotate within the three-phase windings of the stator as the user pedals. The result is a carbon free supply of alternating current that must be first rectified to utility-grade electricity though the built in microinverter in a process explained through Figure 24 below.

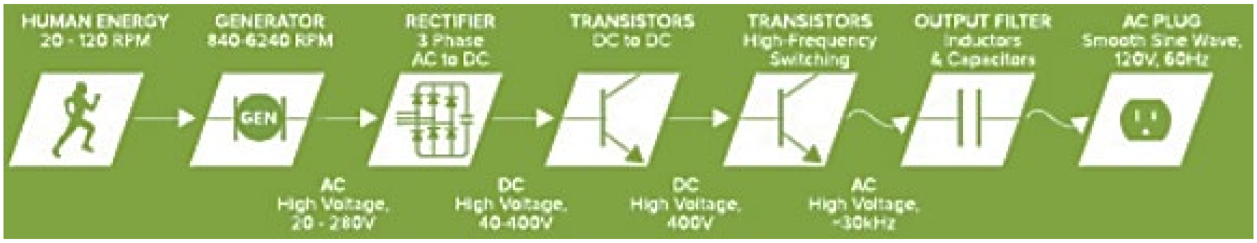


Figure 24 – The process of power generation through SportsArt ECO-POWR technology (SportsArt, 2018).

Before the electricity is ready to be consumed on site, the current produced by the generator goes through a variety of transformations within the microinverter. Figure 24 above portrays the current leaving the generator at a range of 20-280 Volts (V) of alternating current which then gets rectified to direct current at a range of 40-100 V. Next, the current is altered through an initial stage of transistors that is designed to increase the voltage up to 400 V followed by a second stage of transistors that change the direct current back to alternating current. At this point, the frequency of the alternating current is around half of what is required by the building's electrical system; thus, the final step is to filter the frequency through inductors and capacitors to obtain alternating current at 60 Hz. The result is utility grade electricity that can then be fed directly into the electrical system and be consumed onsite to offset the building's electrical load.

All SportsArt EP equipment is designed to produce alternating current at a frequency of 60 Hz, but the amount of power produced is solely dependent on the intensity of the user's workout. The intensity of the user's workout is determined by both the rpm's as well as the level of magnetic resistance being applied against the rotational motion of the flywheel. Power is expressed through Watts (W), and although the three-phase alternators peak production is 350 W, the average user will only produce around half of that in an hour-long workout. On average, over the course of 60 minutes of exercising a user pedaling at 60-70 rpm will produce around 200 W, while an intensified exercise at 80 rpm will produce around 250-300 W, and a below-average exercise at 50 rpm will produce around 120 W (Arriza, 2017).

Due to limited access to documentation, it was unclear how increasing the resistive force for a given RPM would increase power output. However, this process could be explained by using a microinverter switch to redirect some of the electrical current induced in the alternator to increase the current supplied to electromagnets on the rotor. Increasing the current in the electromagnets increases the magnetic field which in turn increases the magnetic flux for any given RPM thereby also increasing the resistive torque while simultaneously increasing power output. The SportsArt EP line can capture anywhere from 60-70% of the energy put into the machine during a user's workout, whereas the remaining 30-40% is used to directly power the fans, consoles, and a heartrate device included in the equipment, or is lost in the form of friction or heat (Arriza, 2017).

In this section the conversion of mechanical energy of a workout into usable electricity was explained; however, this is not a widespread technique. Some of the more sophisticated cardio and strength machines such as NordicTrack Fusion CST and Tonal utilize use magnetic resistance, but these also come with expensive price tags attached. The next sections look at strength training technologies that use magnetic resistance and other related techniques with a view to first understanding how they work and commenting on how they might be modified to generated electricity or not. Before we can cover how strength machines work, we briefly assess the essential elements of the physics related to lifting weights. While this particular section could have been mentioned earlier, we chose to include it here so that it was paired with the discussion of the machines themselves that use magnetic resistance and other techniques.

Part III: Strength Training Using Mass Based and Electromagnetic Resistance Techniques

The physics behind traditional strength training can be understood by Newton's laws of motion. For instance, a ten-kilogram dumbbell that is "at rest" on the surface of the ground "will remain at rest . . . unless it is acted upon by a force" (Britannica, 2020). While this dumbbell is at rest on the surface of the ground, it is subjected to a force equivalent to the product of its mass and the gravitational constant of 9.8 meters per second squared.

$$Force = mass \text{ x } gravitational\ constant$$

$$F = m \cdot g$$

$$F = 10\ kg \cdot 9.8\ m/s^2$$

$$F = 98\ kg \cdot m/s^2 \text{ or } Force = 98\ N$$

If an individual were to exert a force upon the 10 kg dumbbell that is less than or equal to 98 N, the dumbbell will remain at rest. However, if this individual were to now exert a force that is greater than 98 N, the dumbbell will be put into motion and will be accelerated in the direction that that the individual is applying this force. When an individual applies a strategic motion to overcome the moment of inertia of the dumbbell, the individual relies on a unique set of muscles. It is this concept of contracting "specific muscle(s) for a number of repetitions and sets to quickly exhaust the muscle(s) aiming at increasing strength" that defines strength training (Zavadsky, 2012).

When the user lifts the dumbbell, work is done on the dumbbell. Work is defined as the force multiplied by the distance traveled. Because the dumbbell is being lifted in this example, the distance is measured by the height above the surface traveled. The user has now done work on the dumbbell by lifting it, and in doing so, the dumbbell has now gained potential energy associated with the height. Traditional strength training ignores the ability to harness the potential energy associated with lifting weights which could be used to change the magnetic flux within a generator and induce a current rather than go to waste. The formulas below include the potential energy available to do work from lifting the same 10 kg dumbbell a height of 0.5 meters.

$$Work = Force \cdot Distance,\ where\ Force = m \cdot g\ and\ Distance = Height$$

$$W = m \cdot g \cdot h$$

$$Potential\ Energy = m \cdot g \cdot h$$

$$W = Potential\ Energy = 10\ kg \cdot 9.8\ m/s^2 \cdot 0.5\ m$$

$$W = Potential\ Energy = 49\ joules,\ where\ 1\ joule/second = 1\ watt.$$

There are plenty of advantages to using dumbbells while exercising; however, it can be very costly and require a significant amount of space to store a complete set of dumbbells. An affordable and more compact alternative to dumbbells are weight stack machines that that utilize a system of cables, pulleys, and handles to lift a “selectable set of weights” (Olson, 2019). These sets of weights typically begin with a lower limit of 10 pounds (4.5 kg) and through increments of 10 pounds extend to an upper limit around 160 to 200 pounds (Adams, 2021). Just like the description of lifting a dumbbell above, once the user selects the desired amount of resistance on the weight stack, the user must push or “pull on the handle with a force sufficient to overcome the force” of the mass of the weight stack against the force of gravity (Olson, 2019). The handle gives the user a safe and functional region to grip and apply a force, while the cable is used to transfer the force from the handle to the weight stack, and the pulleys are used to “direct the movement of the cable and carry a portion of the resistance mechanisms load” (Olson, 2019).

Because the cable is taut, once the user displaces the handle, the cable and the weight stack are subsequently displaced.

The main purpose of this cable-pulley system is to allow the user to apply a force in a direction that can be translated to a machine. The provides the flexibility for the user to apply a force in a variety of directions while the weights only move vertically along a fixed track. A force diagram is included in Figure 25 below to depict the basic function of these weight stack machines where F' is the direction of the force being applied, a is the direction the weight stack is being accelerated, M is the mass of the weight stack, and Ma is the acceleration of the weight stack, and Mg is the and the acceleration due to gravity (Norrbrand, 2007).

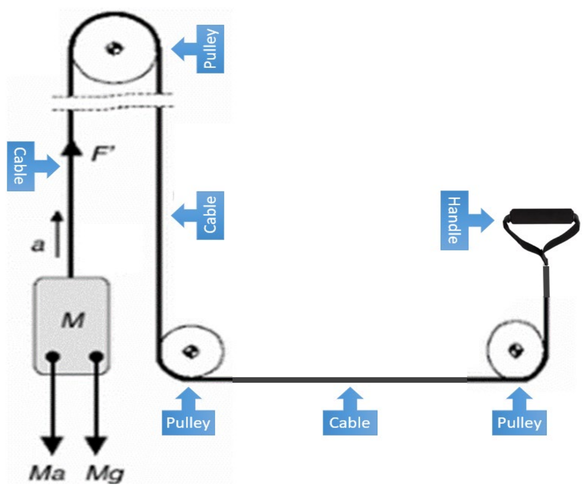


Figure 25 – Force diagram of weight stack machine with labels (Norrbrand, 2007).

Recently, some gym equipment manufacturers are eliminating the need for these weight stacks and are instead utilizing digital weights which simulate the resistance that traditional weights offer but focus on electromagnetism to create this resistance. Two popular designs that are currently available on the market and boast this digital weight function are the NordicTrack Fusion CST and Tonal. In the next two sections we will explain how both technologies work.

Part IV: NordicTrack Fusion CST

In a similar fashion as the cardio machines discussed above, the engineers of the NordicTrack Fusion CST (NordicTrack FCST) have effectively incorporated resistance due to electromagnetic induction into a hybrid strength training machine. Unlike SportsArt EP which uses pedals and cranks to transfer the motion to the flywheel, the NordicTrack FCST uses a cable-pulley system to transfer the movement from the user to put the flywheel into motion. Just as the cardio machines are intended to be used for prolonged periods of time without breaks, NordicTrack FCST's flywheel design offers a similar function making this hybrid strength training machine ideal for High-Intensity Interval Training, or HIIT. This style of training can be described as a combination of cardio and strength training style of exercising as it focuses on burning calories and strengthening muscles while saving time by "cutting down workout times and maximizing effort for even better results than a regular workout" (NordicTrack, 2021). From Figure 26 below, this design comes with six, fixed handle locations giving the user the freedom to perform "130 HIIT workouts" (NordicTrack, 2021).

Figure 26 – NordicTrack Fusion CST multifunctional design (NordicTrack, 2021).

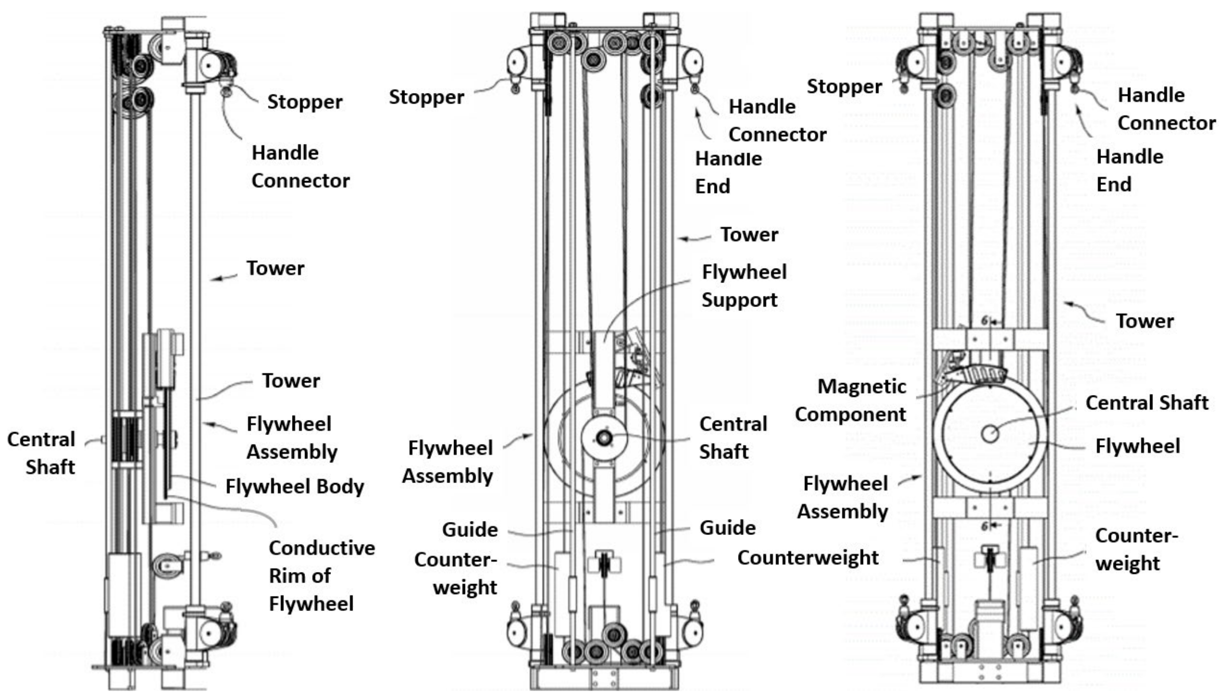
The focal point of the NordicTrack FCST is the Inertia-Enhanced Flywheel mounted on a central shaft near the middle of the tower (NordicTrack, 2021). The patent claims that this flywheel can either "include a relatively dense ferrous component to impart a desired level of rotational inertia to the flywheel," or "may also include a nonferrous component to provide increased braking resistance when used with a magnetic brake mechanism" (Dalebout, 2019). Another version claims this flywheel could have both with "a portion that is formed of cast iron (a ferrous material) to provide the desired rotational inertia with another portion formed of an aluminum material (to provide increased braking response to the magnetic mechanism)" (Dalebout, 2019). While copper is usually used as the conductor in power generation technologies, aluminum is another affordable and abundant conductor used to carry an electrical current. To achieve this braking response, the NordicTrack FCST design utilizes a familiar feature found in both Faraday's Wheel and the cardio machine in Figure 20 above.

The magnetic resistance feature of NordicTrack FCST requires that the flywheel interacts with a magnetic component. Just like the cardio machines previously discussed, a conductive, rotating flywheel experiences a "damped" effect when interacting with a magnetic field (Olson, 2019). This effect is analogous to forcing the spinning flywheel through a "viscous medium," thus applying "resistance to the rotation of the flywheel during a workout" (Olson, 2019). The NordicTrack FCST allows the user to select from 20 different levels of resistance which is accomplished by altering the distance between the flywheel and the magnetic component.

According to the patents available, there are a variety of versions that each perform the same function of applying a magnetic field to a rotating flywheel. One version of the design calls for electromagnets so that the magnetic component can "remain at a fixed distance from the flywheel" and alter the magnetic flux "by providing a greater electrical input to achieve a greater magnetic output" (Olson, 2019). Another version explains this adjustable resistance feature as a magnetic component that can "be moved towards or away from the flywheel with a linear actuator" (Olson, 2016). Due to the transparent design characteristics of the NordicTrack FCST, the user can "see the magnetic plate move further down the flywheel" when the resistance setting is increased (Treadmill Reviews, 2020). For both these versions, the flywheel is configured within a "U-shaped bracket having two sides defining an open slot" in which a magnetic field can be applied to both sides of the rotating flywheel (Dalebout, 2019). According to Dalebout, this design feature is a referred to as a magnetic or eddy current brake (2019).

In addition to utilizing magnetic resistance, virtually tracking a user's workout is an integral characteristic that separates NordicTrack FCST from traditional strength training machines. To accurately monitor qualities of a workout such as calories burned, only the input energy can be included in the calculations. This is managed by only allowing the flywheel to spin "in a single direction regardless of the direction that the pull cable is moving" and utilizing sensors to track the revolutions (Olson, 2019). There are a variety of components in the different versions of the design that can be implemented to ensure that "the return movement of the cable does not affect the calorie count" by the sensors. (Olson, 2019).

One version utilizes spool assemblies that are "coaxially mounted around the central shaft" with the flywheel (Olson, 2019). Each handle is linked to a corresponding spool, or otherwise known as subassembly, with a cable. With bearings included within the subassemblies and mounted concentric "to the central shaft" the user can "transfer a rotational load . . . to the flywheel" while exercising (Olson, 2019). Another integral piece to these subassemblies is the use of a counterweight which aids in the efficient return of the handle after it has been pulled away from the machine. These counterweights operate by being lifted as the user pulls on the handles and unspools the subassembly. Because these counterweights have mass, gravity will then impose a “tangential force” in the opposite direction of the rotating flywheel when the counterweight is returned to the surface causing the handle to spool back onto the subassembly (Olson, 2019). The bearings of the subassembly “are not positioned to transfer the rotational load” caused by the counterweights; thus, the flywheel keeps rotating in a single direction as “no rotational load is transferred to the flywheel” as the handles are returned to the original position (Olson, 2019). Figures 27(a), 27(b), and 27(c) below are labeled diagrams of the main components of the different versions of the NordicTrack FCST.

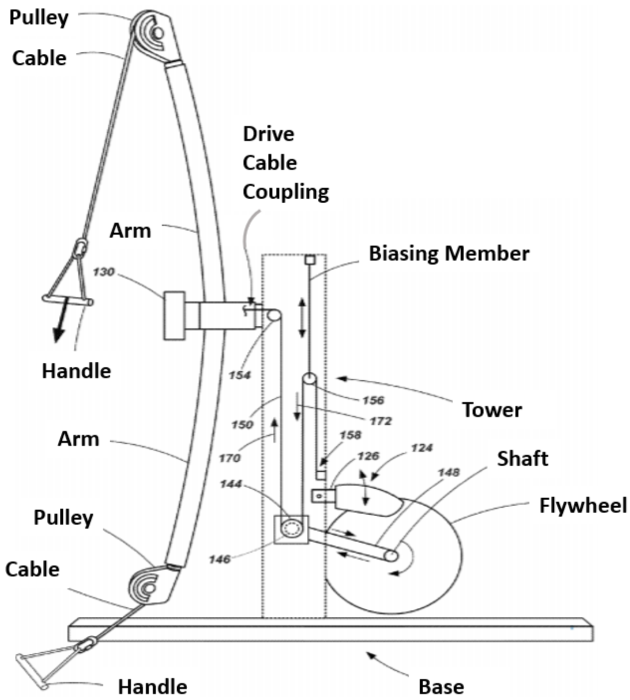


27(a) 27(b) 27(c)

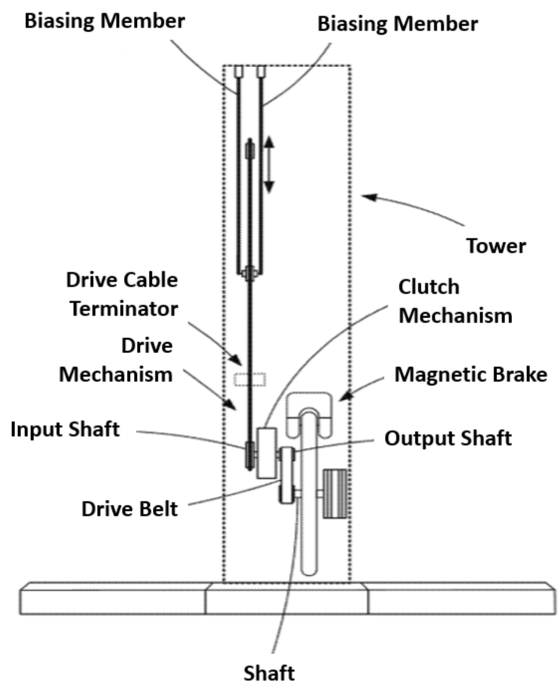
Figures 27(a) – 27(c) – NordicTrack Fusion CST diagram featuring subassembly and counterweight version. (Olson, 2019).

Another version relies on a clutch, a drive belt, and a biasing member to ensure the flywheel only rotates in a single direction. This clutch mechanism fulfills a similar role as the subassemblies and counterweights described above, but instead is designed to enable the flywheel to continue rotating and "not reverse direction" (Dalebout, 2019). Typically, exercise equipment employ sprag clutches for this purpose which transfer rotational energy in one direction, but not the other. These clutches operate much like a ratcheting wrench hand tool which allows the user to crank in one direction and freely spin in the other. The NordicTrack FCST clutch mechanism operates in a similar fashion and would be mounted a separate shaft from the flywheel. Just like the design of SportsArt EP, connecting these two shafts is a drive belt to transfer rotational energy. As the user applies a force to the handles, a pulley cable wrapped around the clutch is displaced causing the clutch to transfer rotational energy to the flywheel through this drive belt.

To efficiently return the handle and pulley cable to its original location, a biasing member is used to reel the cable back around the clutch. The biasing member is "configured to stretch in order to allow the third pulley to be displaced" down the tower of the machine (Dalebout, 2019). The elasticity of this biasing member will then pull this third pulley back up when the user stops applying the force which drives the clutch in the opposite direction to reel the cable back around and return the handle to its original location. Each of these components can be found in Figures 28(a) and 28(b) below. While the design featured in Figures 28(a) and 28(b) below is visually different design than the actual product depicted above in Figure 26, it is a patent of the same inventors behind the NordicTrack FCST and included to provide another version of a potential drivetrain design.



28(a)



28(b)

Figure 28(a) and 28(b) – Side and rear view of one version of the NordicTrack Fusion CST. (Dalebout, 2019).

Table 1 - Explanation of numbered components in Figure 26(a)

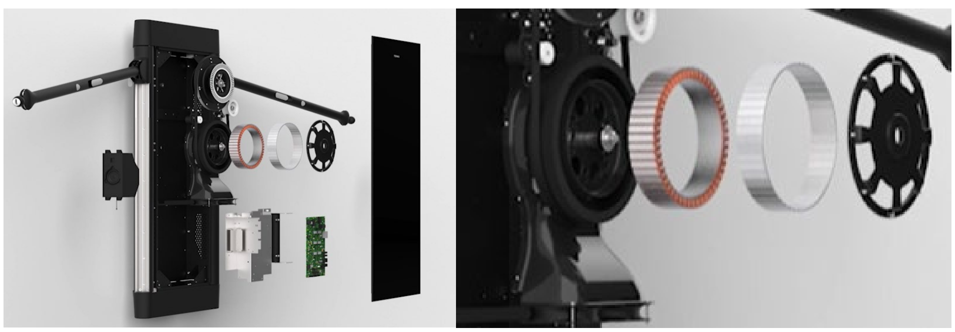
Labeled Number	Component
124	Magnetic Brake
126	Pivoting Arm of Magnetic Brake
130	Control Panel
144	Input Shaft
146	Output Shaft
148	Drive Belt
150	Drive Cable
152 & 156	Drive Pulley
158	Drive Cable Terminator
170 & 172	Direction of Cable Displacement During Exercise

The NordicTrack FCST design has proven that the concept of replacing traditional weight stack machines with digital weights can be accomplished with a flywheel and a magnetic unit. Although the NordicTrack FCST is only able to achieve a weight stack equivalent of "up to 100-pounds," this machine is intended for HIIT training rather than strength training (Amazon, 2021). According to one of the patents, the work done by the user during their HIIT training could be used to power "a battery or an electric generator device," but there was no further information available that expanded on the design harnessing any of the induced currents in the flywheel by the NordicTrack FCST (Olsen, 2016). Considering the device requires an external power source, one can assume the NordicTrack FCST is not engineered to be a net power producer and some, if not all, of the current produced in the flywheel would be expelled as heat and friction. Next, we will analyze a different exercise machine that also utilizes power generation technologies within its design.

Part V: Tonal

Another home gym manufacturer, Tonal, has found an innovative approach that can fulfil a similar role as the NordicTrack CST, but in a more compact design. The engineers of Tonal focused their design on a form of magnetic resistance that also provides the user with the freedom to execute over 170 different training exercises (Panelli, 2020). The following sections will provide a detailed explanation of the components within Tonal's design as well as an overview of how it is operated.

Tonal's design is unique in the sense that it completely replaces the traditional weight stack with a motor that can simulate twice as much resistance as the NordicTrack FCST with "200 pounds of resistance force" (Valente, 2019). As previously mentioned, electromagnets can replace the role of magnets in a generator, thus the same is true for replacing electromagnets on the motor of a magnetic resistance exercise machine. The result is known as electromagnetic resistance and it is centered around using a motor to create resistance. Specifically, a "pancake motor" is used which is a "special variation of the DC motor" (Collins, 2016). The pancake motor design "takes advantage of a flat construction principle with an axial air gap" compared to the more common cylindrical motor which have "a radial air gap" (Collins, 2016). Figure 29(a) below is an explosion diagram of Tonal's design with a zoomed in image of the pancake motor included in Figure 29(b). Additionally, Figure 30 below of an explosion diagram of a pancake motor with the components labeled is included.



29(a) 29(b)

Figures 29(a) and 29(b) – Explosion diagram of Tonal's design 29(a) with a zoomed in image of the pancake motor 29(b) (Tonal, 2020).

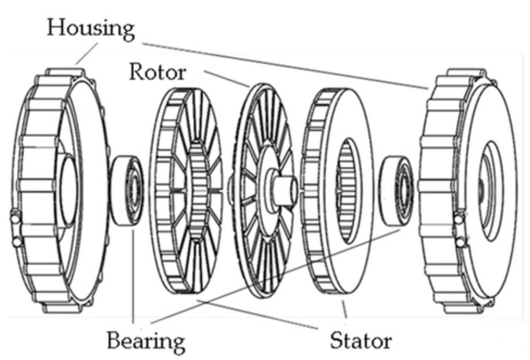


Figure 30 – Explosion diagram of a pancake motor (Collins, 2016).

Pancake motors are well suited for exercise equipment for several reasons. First, the axial design fits all the components into a housing with a “very compact footprint” (Collins, 2016). Second, this compact feature provides for “low inductance” which allows rapid flows of current into the rotor for “virtually instant torque” (Collins, 2016). Third, much like the generators designed for high torque and slower speeds on hydropower plants, pancake motors can be designed in an “out-runner configuration” with “a larger magnet and pole count” making this application suitable for exercise equipment (Valente, 2019). The result of these qualities is that Tonal can create a highly interactive and efficient workout within a low-profile appearance that resembles a flat screen TV as seen at the far left of Figure 31 below.

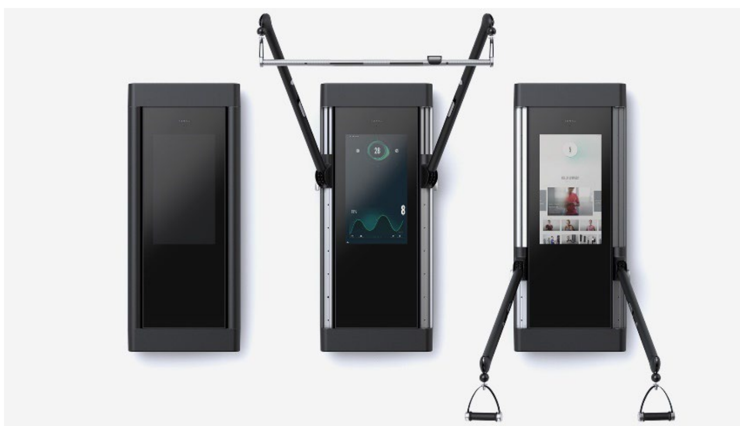


Figure 31 – Tonal’s multifunctional design. (Whipsaw, n.d.).

Much like the SportsArt EP and NordicTrack FCST, the documentation with clear explanations of how Tonal operates were not readily available. The online materials and patents offered some insight, but with different versions of how the machine could potentially operate. In this sense, part of this project has been to sift through these patents to best determine how the machine operates, even though there may be some uncertainty, particularly given patents often contain several designs. The manufacturer claims that the design “employs an electromagnetic resistance engine," where this engine is a "combination of computer chips, coils that generate an electromagnetic field controlled by those chips, and magnets that allow you to fight that [electromagnetic] field as you pull on a cable" (Tonal, 2018). Thus, Tonal provides the user the ability "to digitally manipulate that electromagnetic field" which simulates the experience of a variable resistance weight stack machine (Tonal, 2018).

The patents explain a different function of Tonal in a version that is similar to the Flywheel Energy Storage System in Figure 16 above. As previously discussed, motors are inherently the inverse of a generator, thus the system requires electricity to perform any work. This process begins with the user selecting the desired amount of resistance and entering into Tonal's touchscreen system. This resistance is then generated by the power control system, or controller, which feeds a calibrated amount of current into the windings of the stator. Figure 32 below is included to show the configuration that connects the controller to the motor.

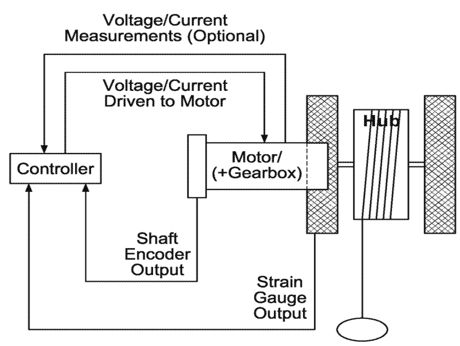


Figure 32 – Diagram of the controller and motor configuration of Tonal (Orady, 2020).

When the stator windings are supplied with alternating current, they will produce a rotating magnetic field (RMF) around the stator. This RMF then induces a rotational force, or torque, upon the rotor in the counterclockwise direction. An increase in the current supplied to the stator equates to a stronger RMF around the windings which results in the user experiencing more resistance. The user must then overcome this torque by applying a force that is greater than the torque of the motor and cause the motor to spin in the clockwise direction. Much like the explanation above of putting a ten-kilogram dumbbell into motion, Tonal's design requires a specific amount of force to spin the motor in the clockwise direction. The difference is that the moment of inertia in Tonal is generated by the torque of the motor rather than just the mass of the dumbbell and the force of gravity. By employing the basics of electromagnetism, Tonal has essentially transformed the exercise industry by reimagining the concept of strength training.

Including electromagnetic resistance technology into Tonal is clearly a relatively new approach for strength training equipment whereas the cable-pulley system portrayed in Figure 31 above, is a much more common design feature in exercise machines. The handles are clearly intended for the user to grip onto, which also represents the terminal end of the component known as the actuator. The user then pushes or "pulls on actuators" while the "machine creates/maintains tension" on the cable (Orady, 2020). On the end opposite of the handle is a spool of cable which is coupled to the motor. The patent for Tonal's design does not clearly indicate exactly how the spool is coupled, rather three different versions are included.

The first version claims that the spool is "directly coupled" to the motor by wrapping "around the body of the motor" so that as the spool unravels from the user applying force to the handles, the "entire motor rotates" (Valente, 2019). In other words, "the body of the motor is being used as a cable spool" in a direct drive configuration (Valente, 2019). In the second version, the spool of cable is coupled to the motor "via a shaft" (Valente, 2019). This is consistent with Figure 32 above where the spool is labeled as the "hub" and the line and oval protruding towards the bottom of the page represent the cable and handle. One noteworthy difference is that the second version also gives the design the flexibility to "add a step-up or step-down ratio” through a gearbox, which is also consistent with the labels of Figure 32 above (Valente, 2019). The third version also uses a shaft to connect the spool to the motor, but it includes an additional spool. This design feature of using two spools, one for each actuator, allows the motor to “split or share the power between the two spools” while also giving the freedom to include a gearbox (Valente, 2019). Figure 33 below depicts the third version while Table 2 below provides an explanation of each component and its respective number.

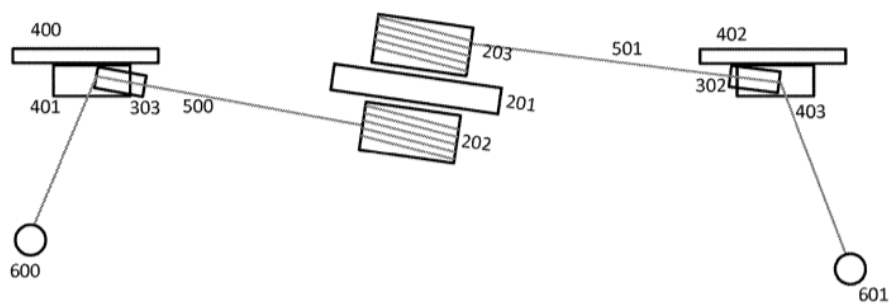


Figure 33 – Top view of third version of Tonal’s design (Valente, 2019).

Table 2 – Explanation of numbered components in Figure 31

Labeled Number	Component	Function
201	Belt Sprocket	Couples the spools of cable to motor
202 & 203	Spools	Takes cable in and releases cable out
302 & 303	Pulley	Guides the cables to engage perpendicularly to the axis of rotation of the spool
400 & 402	Track	Guides the sliders
401 & 403	Sliders	Permits the user to adjust height of arm
500 & 501	Cable	Translates tension of motor to handles
600 & 601	Handles	Allows the user to apply grip and direct a force

Just like the dual nature of the Flywheel Energy Storage System of Figure 16 above, Tonal is also capable of both consuming and producing power. Tonal consumes roughly 1000-1500 Watts when the pancake motor is applying a torque and creating resistance which maintains tension on the handles by not allowing the cable to become unspooled (Valente, 2019). This is portrayed on the far-right side of Figure 31 above where the handles have no slack at all because the motor is sustaining tension on the cables. A user could essentially change the function of the pancake motor to become a pancake generator by gripping onto the handles and curling them upwards to their chest. Assuming the user applies enough force to the handles to overcome the torque of the motor and causes the cable spools to "rotate clockwise" and "unspool," the result will be the production of electricity (Valente, 2019).

Causing the motor to spin in the direction that it is resisting rotation puts the motor into a state called "back-driven" (Valente, 2019). It is only in this back driven state that the cables will begin to retract which causes Tonal's system to undergo power production as the rotation of the rotor is causing the magnetic flux to change within the conducting stator windings. For the user to continue their workout requires them to return the handles back to the original position and start the set all over again. Once the user stops applying enough force to overcome the torque of the motor, the motor returns to its power consuming function and reapplies a torqueing motion in the "counter-clockwise" direction which reels the spool of cable back in (Valente, 2019). Once the handles return to their original position, the user can repeat the process. Each repetition causes Tonal's system to switch from a motor to a generator and back to a motor again, all while helping the user build muscle through strength training.

Tonal requires a constant power source to operate as a motor, but additional components are necessary for when the system is operating as a generator. Interestingly, a professional athlete has an "average power output capability" of nearly 400 Watts sustained for one hour during a cardio workout (Valente, 2019). Alternatively, during a strength training workout, the same professional athlete can generate an "instantaneous power" influx of nearly 10 times the amount that a cardio workout would generate (Valente, 2019). To account for this quick inrush of electricity, Tonal includes an “energy storage device” which is designed to be “charged through use of the exercise machine” (Valente, 2019). Furthermore, the faster and harder the user applies force to the handles equates to an increase in power production (Valente, 2019). Tonal’s patent lists the following technologies suitable for energy storage: lithium ion phosphate battery, lithium ion manganese phosphate battery, AGM sealed lead acid battery, deep cycle battery, marine battery, a capacitor, or a supercapacitor (Valente, 2019). This energy storage device can also be used to supplement the electricity supplied to the motor. This can have the effect of minimizing the load of the building’s circuitry while simultaneously maximizing the torque applied by the motor by more than 20% (Valente, 2019).

This concept of incorporating power generating equipment into Tonal’s design is certainly attractive from a clean energy standpoint, but the current condition of this technology does not qualify as a distributed energy source. In reality, the motor’s demand for electricity outweighs any production that the generator creates. For this reason, an average individual’s hour-long workout is expected to consume around 100 Watts (Tonal Support, 2020).

5. <u>Discussion</u>

Now that the two leading magnetic resistance designs have been explained, this section will begin by comparing and contrasting both the NordicTrack FCST and Tonal. After the advantages and disadvantages of these two designs has been established, this section a proposed design that focuses on affordability, compactness, functionality, and most notably, power production will be provided. Following the proposed design, a brief explanation will be provided to put into perspective the value that the produced electricity from this technology could offer.

Next, the feasibility of this technology will be evaluated to understand the potential uptake of this technology and its applications. This discussion will conclude with future research ideas for energy generating strength training machines.

NordicTrack Fusion CST vs. Tonal

One of the most important concerns when considering home gym equipment is the cost. The NordicTrack FCST has a starting price at $1899 plus a $99 shipping and handling fee (Smith, 2021). Comparatively, Tonal is priced at more than two-thirds the starting price of NordicTrack FCST at a cost of $2745 (Smith, 2021). This is in addition to the $495 smart accessory package for the handle attachments, $43 per month mandatory membership for first year, plus tax, delivery, and installation (Smith, 2021). To make these costs relatively comparable to a monthly gym membership, both NordicTrack FCST and Tonal offer monthly payment options as low as $54 over 39 months ($2106 total) or $149 over 36 months ($5364 total) respectively.

While NordicTrack FCST is more affordable than Tonal, it can only deliver half the total resistance as it is determined to be better suited for HIIT training, thus making it an inferior strength training machine compared to Tonal. Additionally, Tonal allows its users to perform at least 40 more exercises due to the variable arm position, whereas the NordicTrack FCST is limited with 6 arms in fixed positions. However, the NordicTrack FCST is more versatile when considering installation as it can be placed anywhere in a room, whereas Tonal is limited as it needs to be "affixed to a studded wall" (Smith, 2021). Although the NordicTrack FCST has the freedom to be placed in a variety of locations, it may prove to be difficult to move once installed considering it weighs 378 pounds compared to Tonal which only weighs about one-third of the NordicTrack FCST at 130 pounds (Adams, 2021 and Panelli, 2020). Additionally, Tonal offers a more compact feature allowing the arms to be stowed away when not in use compared to the NordicTrack FCST which has a larger footprint. Finally, NordicTrack FCST has more brand recognition with over 45 years of experience in the fitness industry compared to Tonal which appeared for the first time on the market 3 years ago (Consumer Affairs, 2021 and Panelli, 2020). With the clear positive and negative attributes of these two exercise machines under consideration, the following design is proposed to achieve net power production at a relatively affordable cost all while allowing the user the flexibility to perform versatile strength training workouts without demanding ample space requirements.

~~Combining Magnetic Resistance and Strength Training with Linear Generators~~

~~Generating power from rotary motion is not only standard throughout the electric grid, but it is also becoming the potential future standard for exercise equipment as well. The current state of the industry for harnessing electricity from exercise machines is limited to cardio equipment, such as the SportsArt ECO-POWR line, which is designed with rotary generators. Conversely, Tonal is a strength training machine that can produce electricity through a rotary pancake generator, but the power supply does not compensate for the overall power demand causing this design to be a net consumer. Furthermore, the patent of the NordicTrack FCST claims it has the potential to operate with a battery or generator, yet the final product requires external power to function.~~

~~One could argue that Tonal is capable of being a net producer of electricity, but the design is overloaded with integrated features that require more power to operate than the machine can produce. Aside from the pancake motor, these additional power consuming features include: a variable torque controller, video camera with 17 sensors for posture tracking, heart rate detectors, ergo-meter, touch screen display, artificial intelligence computing software, smart~~

~~accessories, Bluetooth capabilities, and speakers (Zavadsky, 2012 and Tonal 2020). The power consuming additional features of the NordicTrack FCST includes: a touchscreen smart tablet, rotary sensor, accelerometer, tracking system with processing and memory resources, energy tracker, WIFI connectivity, camera, and an external audio device (Olson 2019 and Dalebout, 2019). Even the SportsArt EP designs incorporate a console, three-speed fan, heart rate monitor, and a software system to track user activity (Arriza, 2017). The net impact is of these additional features on the SportsArt EP is a contribution to the 30-40% loss in power production as these all influence parasitic losses (Arriza, 2017). Rather than focus on providing the user with a glamorous and interactive experience, the following proposed design focuses on encompassing simplicity with a goal of maximizing net power production.~~

~~Much like the Shake Light previously discussed, one unique solution could resemble a scaled-up version of this handheld flashlight to maintain a simple design. This concept of incorporating linear generators into exercise equipment could be better suited for capturing the energy of a strength training workout. Rotary generators have been found to be well matched with cardio machines for exercises characterized with longer durations and repetitive motions, whereas strength training is commonly associated with vertical motions sustained for shorter periods of time. Integrating linear generators into a strength training machine may be better suited for the mechanics associated with this style of exercising. As previously discussed, both Tonal and NordicTrack FCST require complex systems to translate the linear motion of an exercise into rotary motion. Rather, a design which incorporates a linear generator into the drivetrain could be simpler and a more efficient approach to translating the motion. Although strength training is typically associated with free weights, otherwise known as barbells, dumbbells, or kettlebells, a cable-pulley system can prove to not only be extremely functionable~~

~~to promote flexibility for the user, but it also proven to be an effective way to convert the motion of a user's workout into usable electricity as indicated by the widespread use of cable-pulley weight stack machines.~~

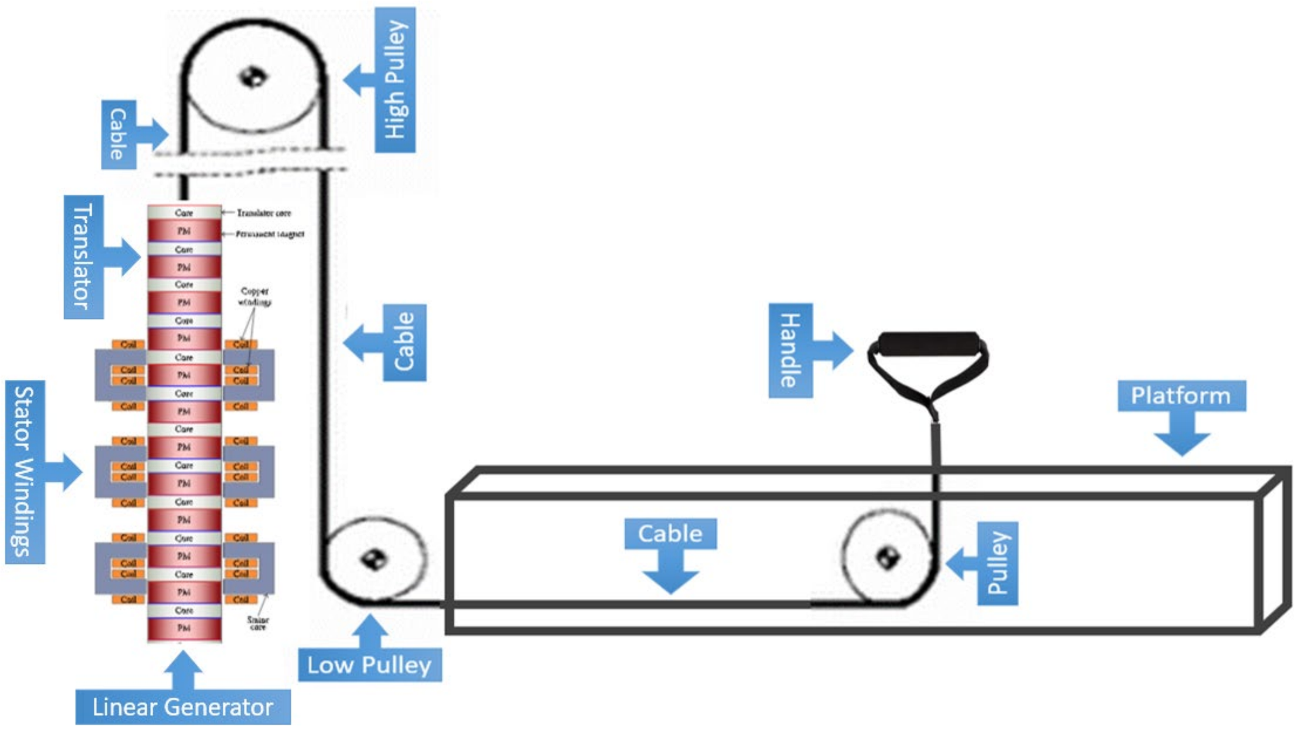
~~In a similar fashion that Tonal and the NordicTrack FCST combined a cable-pulley system with a power generating technologies, this proposed design would instead rely on a linear generator with manual magnetic resistance and gravity to mimic a traditional weight stack. To maximize power output, this proposed design would minimize the inclusion of any nonessential additional features found in Tonal, the NordicTrack FCST, and SportsArt EP. This could be beneficial in reducing any parasitic losses or consumption of electricity by the machine while also providing the user with the freedom to perform countless different exercises. This could allow for any converted electricity to then be repurposed for a vital function of the building.~~

~~Considering air conditioning is the primary contributor to electrical loads for gyms, the previously discussed Ice Bear (Figure 15) could be well suited for fitness facilities (Vega, 2021). Rather than store the electricity in capacitors like the Shake Light, the excess electricity supplied by the energy generating strength training equipment could be dedicated to maintaining the block of ice during normal operating hours of the gym. According to one of the developers of this technology, it requires 5 kW per hour of operation, or 5kWh (Hopkins, 2020). Using the estimates provided by SportsArt, the electricity to power the air conditioning could be completely offset by twenty-five users each producing the average of 200 Wh. This efficient operation of the air conditioning system would not only contribute to user comfortability, but it may even encourage the owners of the gym to keep the central air running without the fear of elevated utility bills. This could prove to be a major advantage in a post-pandemic world where people are more aware of the air they are breathing.~~

The cable-pulley system for this design would require at least three separate pulleys that starts at the surface and ends above the linear generator. Beginning with the handle where the user would apply a push or pull force, it is important that this handle is as close to the surface as possible. Mounting the handle in this fashion is important to maximize the range of motion for the user, but it also allows for the majority of the pulley and cables to covered by a platform. Ideally, the handle would be exposed through ports on a platform protecting the pulley and cable and reducing the risk of a trip hazard. This design feature of mounting the handles in this manner is similar to the design of the Vertimax training system as seen in Figure 34 below. Specifically, the handle location being referred to is labeled by the number three below. Although the Vertimax is intended for more complex, athletic training, the pulley system included in this design encompasses the idea of allowing the user to have a full range of movement as well as covering the pulley and cable under a platform. Unlike the pulley system of the Vertimax in Figure 34 below, rather than guiding the cable to either side of the user, the pulley would be mounted to guide the cable in front of the user.

~~*Figure 34* Handle and pulley locations on Vertimax training system (Vertimax, 2021)~~

~~The next pulley to be incorporated in this proposed design would connect the handle pulley to a pulley located in front of the platform. This pulley, designated as the low pulley, is mounted in the same orientation and at the same height as the handle pulley. The main purpose of this pulley is to direct the cable from the handle to the high pulley. Both of these pulleys are commonly paired together in weight stack exercise machines as seen in the force diagram in Figure 35 below. From Figure 35 below, the low pulley is at the bottom to the right of the linear generator whereas the high pulley is located directly above the center of mass of the linear generator (Norrbrand, 2007). To support the weight of the cable-pulley system and the linear generator, the high pulley would need to be supported by mounting brackets against a wall or upon a structurally sound tower.~~



~~*Figure 35.* Force diagram of high and low pulley of a linear generator strength training exercise machine (Norrbrand, 2007 and Farrok, 2016).~~

~~Rather than allowing the energy input to lifting a weight stack go unused like traditional exercise machines, this proposed design recommends exchanging the weight stack for a linear generator. The mass of the weight stack would be replaced with the magnetic component, or translator, of a linear generator which would not only act as a load to provide the user resistance when exercising, but it could also perform the role of the counterweight found in the NordicTrack FCST. The translator performs the same function of the rotor of a generator, but with vertical motion instead of rotational motion. This is apparent in Figure 36 below where stacks of six-sided permanent magnets are forced to move within coils of copper windings. By purposefully employing magnets in a hexagonal structure, this design can efficiently "generate a three phase voltage system by mounting 2 opposed stators that correspond to each phase with an offset equal to one third of the pole pitch" (Oprea, 2012). Additionally, the hexagonal magnetic~~

structure has the added benefit of "eliminating the radial attraction/repulsion magnetic forces" and effectively increases the total magnetic flux of the translator (Oprea, 2012). Although the Shake Light is inherently less complex than the design of Figure 36, on thing that both designs have in common is that they harness the energy of passing a magnet within conducting coils of copper to produce usable electricity.

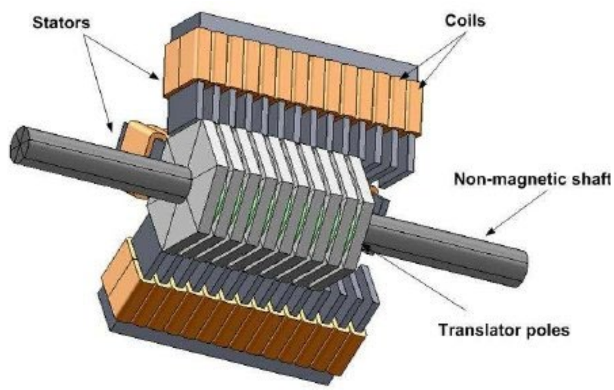
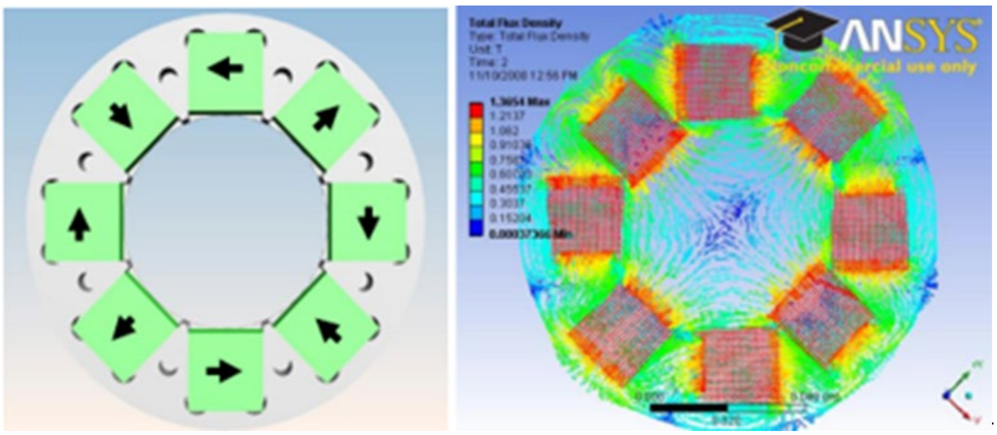


Figure 36 - Linear permanent magnet electric generator with a three-phase stator. (Oprea, 2012).

There is a clear a tradeoff associated with simplicity, complexity, and cost of a linear generator and such analysis is outside of the scope of this report. Additionally, the integration of supplemental power control technologies to safely and efficiently harness the produced electricity are beyond the scope of this project. However, to set the stage for future analysis we will also consider other variants of more complex linear generator systems.

An alternative approach to constructing a linear generator is to surround the stationary coils of copper with a strong magnetic field. The engineers behind the VIVACE hydrokinetic energy converter opted to design their linear generator in this fashion. One notable design feature of the VIVACE is the incorporation of a Halbach Array into the stacks of magnets which "concentrates the magnetic field to a specific location using a predesigned magnet configuration" (Avram, 2008). Because the stator is contained within the translator for this design, increased power production can be obtained when the magnetic field is directly focused upon the coils of copper. This is depicted in Figure 37 below where the magnetic field from the specific arrangement of permanent magnets is strongest as indicated by the concentration of field lines in the center of Figure 37(b).



37(a) 37(b)

Figure 37. Halbach Array of permanent magnets in VIVACE (Avram, 2008).

Although there are a variety of ways to design a linear generator, each design follows the same formula for maximizing power output. The formula states $V_{RMS} = B_e \times U_{av} \times N_e \times I_e$ where the voltage output (V_{RMS}) is the dependent variable in this equation (Oprea, 2012). Thus, if the goal is to increase the voltage output, then this can be accomplished by increasing at least one, if not all, of the following: the magnetic flux density passing through the coil (B_e), the average linear speed (U_{av}), the number of turns or phases (N_e), and the average length of one coil turn (I_e) (Oprea, 2012). The magnetic flux density passing through the coil (B_e) can be increased by: implementing a Hallbach Array as shown in Figure 37 above, using larger magnets, relying on magnets with higher power densities, adding more stacks of magnets, or using stacks of magnets with more pole counts. Considering effective strength training requires slow, controlled movements, the linear speed (U_{av}) can be increased by implementing a gearbox to step up the speed and increase the changing magnetic flux within the stator. Additionally, the number of turns, or switchbacks, within the cables around the pulleys and the diameters of the pulleys themselves can impact the speed of motion translated from the user to the generator. Therefore, the least amount of turns and pulleys of the smallest diameter should be considered to limit the loss of linear speed along the entire pulley system. Finally, increasing the number of turns (N_e) and average length of one coil turn (I_e) can be accomplished by using stator windings with added coils of greater lengths.

The magnetic resistance function of this proposed design is integral to provide the user with flexibility but could also increase overall power production. Because the weight stack will be exchanged for a translator, an added feature that increases the magnetic field will not only create more resistance against the user, but it would also increase the B_e component in the formula above which subsequently increases the voltage output. As previously discussed, Tonal achieved increased resistance by supplying more current to the electromagnets in the stators whereas the NordicTrack FCST increased resistance by decreasing the distance between the magnetic component and the rotating flywheel. Both Tonal and the NordicTrack FCST rely on an interactive system where the user selects a resistance setting and the machine automatically applies the resistance against the user. Adjusting the strength of this B_e component could be accomplished through a variety of methods. Ideally, the user would manually adjust the magnetic field by physically altering the distance between the magnetic component and the stator windings or by adding or removing supplemental magnetic components to interact with a uniform translator. In the event that electromagnets are used to automatically adjust the magnetic field, some electrical output is expected to be consumed by supplying additional current to the

~~electromagnets, but this could be offset by a gain in power output as this will increase the B_e component in the formula above~~

~~A cable-pulley design equipped with a linear generator and a magnetic resistance function could be used as both a complete strength training machine and a distributed energy source. Additional features like fans, speakers, and touch screen digital displays that enhance the exercising experience would not be included as these only contradict the goal of efficiently harnessing and storing the produced electricity to offset the building's load. Rather, the user could enhance the experience by providing a comfortable and well-ventilated environment by powering the facility's Ice Bear from the energy supplied during their workout.~~

Perspective of Value

The exact calculation for how much electricity a strength training machine could produce is unclear at this moment. The engineers behind Tonal claimed that the instantaneous power exerted from strength training is estimated to be 10 times the amount of energy that a cardio workout would generate, although this would be for much shorter bursts or periods (Valente, 2019). SportsArt EP offered third party verified results which provide the best insight by claiming that the average user will produce 200 Watts (W) during an hour-long cardio exercise (Arriza, 2017). Converting these numbers to units of power yields 200 watt-hours (Wh), or 0.2 kilowatt-hours (kWh). To put this amount of power into perspective, an iPhone battery can hold 5.45 Wh, therefore, a user could completely charge a dead iPhone over thirty-times with 200 Wh (Helman, 2013). For larger applications, 200 Wh would be enough to power a laptop for 4-10 ten hours (Silicon Valley Power, n.d.). Even most wide-screen, high-definition televisions can be operated for a few hours a day with a supply of 200 Wh (Silicon Valley Power, n.d.). Additionally, 200 Wh would keep a standard 12 W Light Emitting Diode (LED) bulb lit for over

16 hours (US Department of Energy, n.d.). Alternatively, 200 Wh could keep 16 LED bulbs shining for over one hour.

According to the EIA national electricity rate database, as of February 2021, the average rate of electricity across all sectors was $0.1160 per kWh (2021). Therefore, the monetary value of 200 W for one hour equates to $0.0232, or just over two pennies. While pennies may initially seem like an unfruitful investment to pursue, it is important to remember that these pennies are currently available with minimal competition. Furthermore, the price volatility that characterize fossil fuels in our global supply chain can result in the average cost of electricity to become unstable in a short period of time. Not only is this applicable as fossil fuel reserves are depleted, but this also realized in light of the recent devastating impacts of climate change.

Take for example the failure of the Texan electric grid in February of 2021 during a winter storm that left consumers with rates as high as $9.00 per kWh (Hersher, 2021). A home in Texas equipped with one of these energy generating strength training machines with power storage could have hypothetically warmed a portion of their home for roughly 5 hours through a heat lamp through a 60-minute workout while simultaneously avoiding the inflated cost of electricity from their utility provider (Silicon Valley Power, n.d.). Granted, this was an extreme case; however, more frequent and more extreme weather events are in our forecast from greenhouse gases entering our atmosphere at an unprecedented rate. Energy generating strength training machines are far from a silver bullet that can solve an energy crisis during an extreme weather event, but their value is not negligible.

Feasibility of Technology

In 2019, the global market size of the fitness and health club industry was estimated to be worth $96 billion (Gough, 2021). While SportsArt was evaluating the potential to capitalize on this industry with their ECO-POWR line, they turned to the results of study conducted by The Nielsen Company. The primary results of this study with over 30,000 respondents across 60 countries found that sustainable alternatives are important to consumers, especially among the Generation Z and Millennials (Nielsen, 2015). Furthermore, this study found that sixty-six percent of the respondents claimed to be "willing to pay more for sustainable brands" (Nielsen, 2015). In addition, fifty-nine percent of the respondents also claimed a product's "health and wellness benefits are influential purchase decision drivers," which includes "products that are both good for them and good for society" (Nielsen, 2015). Although this survey did not specifically mention a strength training exercise machine in their questions regarding sustainable product consumption habits, there are some worthwhile applications for this study.

Millennials currently account for the largest population group in the United States. According to Figure 38 below, this is also reflective in the number of active health club members as both Generation Y/Millennials and Generation Z combine for nearly half (47%) of the total active health club members. Considering there are no machines that offer power generation from strength training exercises, this product could fill an outstanding niche in the health and fitness club industry. Additionally, lower-priced competition from traditional gyms that do not harness the energy from exercising may not be as detrimental to the market penetration of strength training machines with energy generation capabilities. Since younger generations can be persuaded to purchase more sustainable products even if they are more expensive, this implies that an energy generating strength training machine could be worth developing even if they cost more than their non-power producing counterparts.

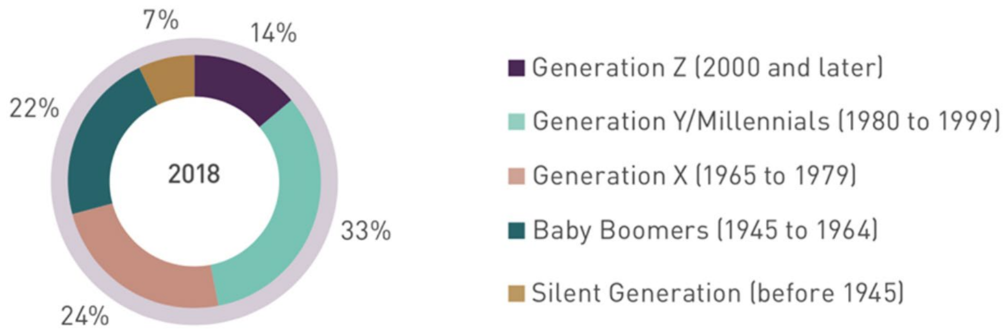


Figure 38– Breakdown of active health club members by generation. (Satagaj, 2020).

Health clubs and home gyms are some of the most appropriate locations to install an energy generating strength training machine, but there are plenty of other suitable sites where this technology can be implemented. Universities are a prime candidate for this technology as the use of their student and faculty fitness facilities usually come at no additional cost to the students. Similarly, high schools could be another location where this technology could be easily integrated. Correctional facilities can even capitalize on the number of prisoners and the energy expended during exercising throughout their sentencing by installing this technology. Additionally, commercial office spaces, multifamily housing, hotels and physical therapy centers all receive a modest amount of foot traffic through their fitness centers which could make each of these locations suitable for energy generating strength training machines.

Future Research

To progress the efforts of this research project, there are a few target areas that could be explored. First, two additional exercise designs have been identified during this research that also use magnetic resistance techniques. Just as we conducted a review of three designs above, the Bowflex HVT and the TANK M1 Sled could both be evaluated to gain an understanding of their drivetrain components and their potential to convert mechanical energy into electricity. Second, because there is no tangible data available that supports the amount of electricity that could be produced from a strength training workout, research and development into a prototype could provide a more accurate account of the potential power output of these machines. This process could be aided by obtaining calculations and completing cost-benefit analyses to gain an understanding of the different effects from implementing a variety of components into a protype. These cost-benefit analyses could include, but are not limited to: flywheels, cables, pulleys, electromagnets, permanent magnets, inverters, energy storage options, and the different magnetic resistance techniques.

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