Dome-Shaped Jungle Gyms and the Spectrin Lattice of Erythrocytes and Cardiomyocytes

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Rule to Build By:
In order to build self-supporting structures, the mechanical forces of tension and compression in the structure of dome-shaped jungle gyms and in erythrocytes and cardiomyocytes need to remain balanced (Morris and Staudinger 2016).

What:
The spectrin lattice of erythrocytes and cardiomyocytes, the microscopic structure for this study, and dome-shaped jungle gyms, the macroscopic structure, both balance mechanical forces of tension and compression.

How:
Dome-shaped jungle gyms, shaped like semi-circular spheres, maintain the ductile and triangular structure through the use of steel bars (refer to figures 1 and 2). This triangular shape provides the mechanical strength necessary for the dome-shaped jungle gym to withstand stress caused by tensile, compressive, and applied forces. When a child plays on the dome-shaped jungle gym, the steel bars contain high tensile strength - the ability to withstand stress that elongates the structures - that can withstand the applied force from the child (Pavlina and Van Tyne 2008). The circular pieces connecting the steel bars contain high-density polyethylene, which provides the ductility necessary for each steel bar to endure the tensile stress induced by pulling the pieces together (Dieter 1986; Plastics Design Library 1997). Furthermore, the circular pieces allow the structure withstand the compressive forces from the steel bars pushing against the pieces because of the polydisperse and resin-like characteristics of polyethylene (Ruiz-Herrero et. al. 2005).

The spectrin lattice, an actin-binding protein formed by connecting individual spectrin strands with cross-linking proteins, lies beneath the plasma membrane of the cell (refer to figures 3 and 4). These cross-linking proteins polymerize the α and β dimer subunits of the spectrin strands (see figure 3). Spectrin strands interlock through the α and β dimers to form the spectrin lattice, which maintains flexibility and can grow to approximately 250 nm in length and 5 nm in width. Cells contain spectrin molecules linked to actin filaments approximately 40 nm in length. Actin filaments bind to the actin-binding domains of spectrin, allowing for binding between actin filaments and the cellular membrane (see figures 3 and 4). In mammals, spectrin functions to link the plasma membrane to the cell interior, to evenly distribute the mechanical forces over the entire lattice, and to organize the proteins responsible for transmembrane communication,
including the sodium/potassium ion channel receptor proteins (Bennett et al. 2004). Along with that, the spectrin lattice maintains the organization and arrangement of transmembrane proteins and lipid asymmetry within the cell. Ankyrin, an adaptor protein, anchors the spectrin lattice to the cell membrane by binding to the β dimer of the spectrin strands (Spectrin 2016). Destruction of the spectrin lattice leads to budding, a process that occurs during apoptosis, or cell death. This lattice upholds to the Rule to Build By because the spectrin strands form triangles that absorb and distribute the stress across the geometric network. By absorbing and redistributing the mechanical forces, this triangular structure allows for the cell to undergo an enormous amount of mechanical stress without damaging the cell (Bennett et al. 2004, Crump 2012, Spectrin 2016).

Erythrocytes, or red blood cells, contain a spectrin lattice structure that forms the biconcave shape of these cells. On average, red blood cells remain approximately 7.5-9 µm in diameter and 1.5-2.5 µm in thickness (Diez-Silva et al. 2010). In red blood cells, the spectrin lattice forms a disc-like structure, which provides the mechanical strength necessary for the cell. Red blood cells maintain a flexible membrane and a high surface-to-volume ratio to help the cells endure the stress of microcirculation (Diez-Silva et al. 2010). When placed under tensile or compressive stress, the mechanical strength of the spectrin lattice acts against the force, maintaining erythrocyte structure without rupturing the cell membrane. Additionally, the spectrin lattice allows these red blood cells to avoid damage from the applied force of the fluid flow within the veins and capillaries (Diez-Silva et al. 2010). Defects in the spectrin lattice of red blood cells could lead to potential diseases, including elliptocytosis, which causes the red blood cells to appear elliptical instead of biconcave in shape (Uniprot Consortium 2016). Furthermore, these defects could lead to the obstruction of microcirculation within the body because the spectrin network provides red blood cells with the ability to flow throughout the body without experiencing damage (Diez-Silva et al. 2010).

Along with erythrocytes, cardiomyocytes, or cardiac muscle cells, contain a spectrin lattice for structural purposes. In cardiac muscle cells, the spectrin lattice arranges into costameres, strands of proteins that cover the sarcomeres. Costameres, the proteins that link the plasma membrane to the cell interior, function to maintain cell adhesions and distribute mechanical forces, specifically contractile forces, across the lattice structure (Bennett et al. 2004). Protein 4.1 allows the spectrin lattice to link with the plasma membrane and endure the mechanical stress of systolic pressure (Taylor Harris et al. 2005). Mutations in the ankyrin protein could potentially cause cardiac arrythmia, a sudden, stress-induced cardiac death due to the inability for the spectrin binds to bind. If the spectrin strands lack the ability to bind, then the spectrin lattice, and ultimately the cell structure, deforms (Bennett and Healy 2008).

**Why:**
The reason a dome-shaped jungle gym can balance forces of tension and compression involves a jungle gym’s ability to easily distribute forces while avoiding destruction. Simple physics can apply to the way man-made structures endure forces of tension and compression without collapsing. Pressure, or the amount of force applied over a certain area, allows for a variety of self-supporting structures to balance forces of tension and compression (Serway and Jewitt 2012). Consider the following physics equation:

\[ \text{Pressure} = \frac{\text{Force}}{\text{Area}} \]
This equation shows that with a constant force of tension or compression, the pressure depends on the area. With a large area, the dome-shaped jungle gym will experience a smaller amount of pressure from the applied force, thus allowing the jungle gym to withstand forces of tension and compression. A larger surface area will thus require more steel bars and circular pieces. More steel bars and circular pieces allow for a jungle gym to absorb and distribute tensile and compressive forces without collapsing because a larger surface area can decrease the pressure load applied to the entire structure. Therefore, larger jungle gym can withstand the applied forces from a child swinging from the steel bars or from the tensile and compressive forces induced by the structure (Pope 2012; Serway and Jewitt 2012).

The spectrin lattice can balance forces of tension and compression through the geometric structure that the lattice provides for the red blood cells. Since the triangular shapes absorb and disperse the stress from the forces across the lattice, the cell will avoid damage. Many eukaryotic cells demonstrate the self-supporting structure of the spectrin lattice, including red blood cells and cardiac muscle cells. Red blood cells experience an immense amount of mechanical stress through tensile and compressive forces in the capillaries and veins (Crump 2012, Diez-Silva et. al. 2010). To avoid damage and ensure delivery of oxygen throughout the body, the spectrin lattice allows these red blood cells to maintain flexibility so the cells can maneuver around blockages (Diez-Silva et. al. 2010). Furthermore, the spectrin lattice allows these cells to withstand the compressive forces induced by the capillaries and veins without experiencing structural damage (Diez-Silva et. al. 2010). If the spectrin lattice contains defects due to mutations, the red blood cells will undergo apoptosis. In addition to red blood cells, cardiac muscle cells contain spectrin, which allows these cells to withstand the stress of mechanical forces. AlphaII-spectrin, a spectrin isoform, remains in the contractile fibers of the cardiomyocytes, allowing the cardiac muscle cells to maintain the structure of cardiomyocytes while under systolic pressure (Bennett et. al. 2004).

Figures:

Figure 1. Dome-shaped jungle gym. The triangle geometry formed by the steel bars allows for the jungle-gym to withstand mechanical and gravitational forces. (Figure from https://www.lifetime.com/gallery/playground/outdoor-play/dome-climbers/101301)
Figure 2. **Circular pieces of structure.** These circular pieces provide the strength necessary for the jungle gym to withstand tensile pressure. (Figure from https://www.lifetime.com/gallery/playground/outdoor-play/dome-climbers/101301)

Figure 3. **The geometric structure of spectrin.** The spectrin lattice contains protein 4.1 for binding spectrin strands together and actin to anchor the spectrin to the plasma membrane. Along with that, spectrin contains other proteins and subunits that help with structure and cellular communication. (Figure from http://en.wikipedia.org/wiki/Spectrin)
Figure 4. Spectrin lattice on plasma membrane. The spectrin lattice remains anchored to the plasma membrane through ankyrin and actin filaments while maintaining a flexible, geometric structure. (Figure from http://www.sigmaaldrich.com/life-science/metabolomics/enzyme-explorer/learning-center/structural-proteins/spectrin.html)

References:


